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**Reshaping Infrastructure: Evidence from the division of Germany**

Marta Santamaria

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# RESHAPING INFRASTRUCTURE: EVIDENCE FROM THE DIVISION OF GERMANY

Marta Santamaria<sup>\*</sup>

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## Abstract

Can governments adjust transportation infrastructure to unexpected economic changes? This paper studies the importance of flexibility in the development of a transport network exploiting the division of Germany. To understand the incentives behind infrastructure construction, I develop a multi-region quantitative trade model with endogenous infrastructure choice and calibrate it to the prewar German economy. I exploit the division of Germany, an exogenous change in borders, to test the ability of the model to predict highway development before and after the division. Using newly collected data, I document that the West German government considerably reshaped the highway network after the division shock. The reshaping of the network increased aggregate welfare by 1.24% to 2.13%. However, this reshaping was constrained by the part of the network developed before the division. I quantify the cost of path-dependence from these pre-division highway links. The ability to reshape the full network could have increased aggregate welfare by an additional 1.86%.

**JEL codes:** F11, O18, R13.

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<sup>\*</sup>University of Warwick and CAGE, Department of Economics, CV47AL, United Kingdom. Mailing address: 35 Greencroft Gardens, Flat 3. NW6 3LN, London. United Kingdom. Email address: marta.santamaria@warwick.ac.uk. I am indebted to my advisor Jaume Ventura for his continued encouragement and guidance. Special thanks to Manuel Garcia-Santana, Joan Monras, David Nagy, Giacomo Ponzetto, Veronica Rappoport and Edouard Schaal; their suggestions and support greatly improved this paper. I hugely benefited from conversations with Isaac Bailey, Andrew Bernard, Alessandra Bonfiglioli, David Levine (discussant), Ana Moreno, Claudia Robles-Garcia, Thomas Sampson, Daniel Sturm, Catherine Thomas, Jagdish Tripathy and Elisabet Viladecans-Marsal. I thank seminar participants at Universitat Pompeu Fabra, the International Economics workshop at LSE, the IEB Urban Economics workshop 2018 and the 2018 EDP at EUI for many useful comments. Financial support from the Generalitat de Catalunya and Caixa Bank is gratefully acknowledged. All errors are my own.

# I INTRODUCTION

Governments throughout the world spend large amounts of money on developing transportation infrastructure. Expenses on the category of transport and communications have averaged 2% of GDP annually in OECD countries in the last three decades ([Sutherland et al., 2009](#)). In 2019, 18% of the World Bank Group lending was devoted to transportation.<sup>1</sup> Infrastructure projects are also extremely long-lived: the average lifespan of highways is twenty years, while the average lifespan of railways and airports is over forty years ([Rodrigue et al., 2013](#)). This raises the question of whether governments can adjust transportation infrastructure to unexpected economic changes and how large are the aggregate costs of not being able to do so. Quantifying these costs presents an empirical challenge since alternative infrastructure proposals cannot be evaluated with experimental methods.<sup>2</sup>

This paper exploits an unexpected change in borders, the division of Germany, together with a quantitative spatial model to study the importance of flexibility in the development of a transport network. The fundamental idea behind my approach is that the construction of the German highway network started in the 1930s, when the abrupt separation of West Germany from East Germany was unanticipated ([Redding and Sturm, 2008](#)). Construction progressed following a country-wide highway Plan until it was interrupted by the Second World War. Figure I represents the highway network in the year 1949, when the German state was divided. As we can see, the new border cut across many of the newly built highways. I study how the division affected highway construction in West Germany. Using historical digitised maps, I document that highway construction before the division followed the government's prewar Plan without deviation. After the division, however, half of the highways built deviated from the prewar Plan. In particular, highway construction shifted to the West and followed predominantly a North-South direction.

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<sup>1</sup>The World Bank Group. Annual Report, 2019. Lending Data.

<sup>2</sup>This empirical challenge to evaluate the economic impact of transport infrastructure has been addressed in the literature by exploiting different sources of exogenous variation in local access to infrastructure, reviewed in [Redding and Turner \(2015\)](#).

## [FIGURE I]

To investigate this change in the pattern of highway construction, I develop a quantitative spatial model with endogenous infrastructure. The model features a set of locations connected by the transport network and mobile workers with heterogeneous preferences across locations. In each location, monopolistically-competing firms produce an endogenous measure of differentiated varieties in the spirit of [Krugman \(1980\)](#). These varieties are traded between locations subject to transport costs. The model builds on the family of quantitative spatial models reviewed by [Redding and Rossi-Hansberg \(2017\)](#) and is specially close to [Redding \(2016\)](#). I make two extensions to this framework. First, I propose a new transport cost function that incorporates infrastructure quality. Second, I introduce a benevolent government that chooses infrastructure to maximise aggregate welfare, subject to the spatial equilibrium conditions. I propose a solution algorithm that leverages the model's nested structure and use it to solve for the efficient infrastructure investment.

I assess whether the model's qualitative predictions can explain the reshaping of the highway network after the division. The model predicts that infrastructure investments in a location increase with the trade intensity of the location (*size*) and with the flow of trade that transits the location (*centrality*). According to these predictions, infrastructure investments should be reallocated when the volume of trade or transit changes. The division of Germany affected both the trade volume and the transit of goods between East Germany and West Germany. Consistent with the historical data, the model correctly predicts that locations near the new border, the ones that received the largest shock, should be allocated less infrastructure after the division.

To further explore the model's quantitative predictions and perform counterfactuals, I take the model to the data. My strategy is to fit the model to Germany before the division. First, I calibrate the spatial equilibrium parameters and transport costs using Germany's population and road network in 1938, eleven years before the division. Second, I estimate the key structural parameter of the model, the returns to highway investments, that controls the concentration of investments across locations. To estimate this parameter, I match the asymmetry of highway concentration in the prewar

highway Plan using Simulated Method of Moments. Before evaluating the model's predictions, I confirm that the spatial equilibrium is correctly calibrated both before and after the division. Using newly collected data on traffic of goods, I show that the model can predict trade flows before the division, and population and trade flows after the division, expanding previous findings in [Redding and Sturm \(2008\)](#).

After checking the economic geography predictions, I show that the model is able to explain highway development over time. First, I use the model to solve for the efficient highway network before the division. I compare it with a prewar highway plan designed by engineers three years before the ascent of Hitler to power. The model's solution explains the main patterns of investment across districts in the prewar Plan. Second, I test the ability of the model to predict new highway investments after the division. To do this, I simulate the division in the model and re-compute the infrastructure allocation in West Germany. The model can capture the highway reshaping patterns after the division shock: larger investments near the western border and in a North-South direction. The change in transport costs implied by the predicted highway network accounts for 97% of the variation in transport costs in the data (computed using the actual highway network in West Germany). The ability of the spatial model to capture shifting priorities in highway development supports the incorporation of spatial models to the economic policy toolbox.

I perform two counterfactual exercises to quantify the importance of flexibility in the development of transport infrastructure. First, I use the model as a measuring tool to calculate the gains from reshaping the highway network. After the division, highway construction significantly deviated from the prewar highway Plan. My results suggest that the reshaping of the network increased aggregate welfare by 1.24% when compared to the counterfactual construction of the prewar highway Plan. These welfare gains increase up to 2.13%, when I account for the beginning of the European integration process. These improvements come from deviations from the prewar Plan, while keeping the length of the highway network constant. The advantage of this exercise is that it is independent of the model's solution for efficient infrastructure. It is computed from

the spatial equilibrium of the model that is common across most quantitative spatial frameworks (Redding and Rossi-Hansberg, 2017).

Finally, I explore whether the highways built before the division constrained the overall efficiency of the transport network. These prewar investments created initial conditions for the West German government and could have affected future highway development due to path-dependence. To understand this, I use the full-structure of the model. First, I solve for the unconstrained infrastructure network in West Germany, assuming that no highway had been built before the division. Then, I compare it with the constrained infrastructure network that takes pre-division highways as given. I find that aggregate welfare is 1.86% higher under the unconstrained network. In terms of magnitude, these gains represent 11% of the total gains generated by the complete highway network. This is to the best of my knowledge the first quantification of the aggregate cost of path-dependence in the literature.

The German division provides two unique advantages to study whether governments can adapt infrastructure to unexpected changes. First, it was a large-scale geographic shock that redefined the incentives to allocate infrastructure. Second, the West German government faced some rigidity that prevented a complete reshaping of the network. While this paper explores the division period, the staggered development of the transport network also required a large infrastructure expansion after reunification. The reunification infrastructure plan consisted of seventeen projects (highways, railroads and waterways) that the German government developed to reconnect East Germany and West Germany after decades of separation.<sup>3</sup> My findings reveal that path-dependence from past infrastructure investments can create high aggregate costs. These costs will be particularly relevant in the context of fast-changing emerging economies.

Policy-makers and academics, encouraged by the growing availability of spatial data, have increased their efforts to understand how to better allocate infrastructure investments. There is an extensive literature on the economic effects of infrastructure. A first and growing group of

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<sup>3</sup>The German Unification Transport Projects, Verkehrsprojekte Deutsche Einheit (DVT) presented on April, 1991.

papers has focused on the effect of infrastructure access on local outcomes (for example [Donaldson \(2018\)](#) on prices, [Michaels \(2008\)](#) and [Duranton et al. \(2014\)](#) on specialisation, [Faber \(2014\)](#) and [Banerjee et al. \(2020\)](#) on output).<sup>4</sup> More recently, research has analysed the aggregate effects of infrastructure investments using quantitative models (for example [Donaldson and Hornbeck \(2016\)](#), [Allen and Arkolakis \(2019\)](#) and [Nagy et al. \(2020\)](#) for the US, [Asturias et al. \(2019\)](#), [Donaldson \(2018\)](#) and [Alder \(2019\)](#) for India, [Balboni \(2019\)](#) for Vietnam and [Morten and Oliveira \(2018\)](#) for Brazil).<sup>5</sup> This paper contributes to this second strand of papers by quantifying the aggregate effects of reshaping the German highway network in the aftermath of the division. This question is most closely related to [Balboni \(2019\)](#), that studies the benefits of coastal road construction in Vietnam, and to [Alder \(2019\)](#) that analyses the distributional effects of different configurations of the Indian highway network. My contribution is to incorporate the investment decision in the quantitative spatial model. This unified approach allows me to solve for the efficient infrastructure allocation together with the spatial equilibrium. Consistent with these papers, I find that the specific placement of the network considerably affects aggregate income and welfare.

The results of this paper also contribute to the literature on the role of history in shaping economic activity, such as [Davis and Weinstein \(2002\)](#) on the effects of wartime bombings in Japan on city size, [Redding and Sturm \(2008\)](#) on the effects of the division of Germany on city growth and, most recently, [Ahlfeldt et al. \(2018\)](#) on the effects of the division of Berlin on agglomeration.<sup>6</sup> Infrastructure investments, being long-lived, can act as a mechanism that perpetuates the effects of shocks through path-dependence. Counterfactuals in this paper reveal that prewar highway investments acted as an initial condition and shaped post-division investments. My contribution to this literature is to compute the aggregate cost of path-dependence, while previous studies

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<sup>4</sup>Other examples are [Baum-Snow et al. \(2017\)](#) on output, [Atack et al. \(2011\)](#) and [Ghani et al. \(2016\)](#) on firm size, [Möller and Zierer \(2018\)](#) on employment, [Baum-Snow \(2007\)](#), [Duranton and Turner \(2012\)](#), [Garcia-Lopez et al. \(2015\)](#), [Baum-Snow et al. \(2017\)](#) on population growth.

<sup>5</sup>Other relevant studies have looked at the effects of infrastructure on commuting patterns and sorting such as [Tsivanidis \(2019\)](#) on the construction of the TransMilenio in Bogota, [Heblich et al. \(2020\)](#) on the construction of the railway in 1920's London and [Robert-Nicoud et al. \(2019\)](#) on the effects of highway on spatial sorting in Switzerland.

<sup>6</sup>Other related studies include [Brulhart et al. \(2012\)](#) on the effects of the Fall of the Iron Curtain on the adjustment of wages and employment in Austria and [Redding and Sturm \(2016\)](#) on the effects of the London Blitz on local economic outcomes at the neighbourhood level.



have focused on the relative effects of path-dependence across units ( for example [Bleakley and Lin \(2012\)](#)). This paper provides the first estimate in the literature of the aggregate cost of path-dependence, that amounts to 1.86% of aggregate welfare.

Finally, this paper is related to a very recent strand of the literature that studies the endogenous choice of transport infrastructure. [Allen and Arkolakis \(2019\)](#) model endogenous infrastructure as the result of decentralised decisions of idiosyncratic traders. By contrast, [Felbermayr and Tarasov \(2019\)](#), [Fajgelbaum and Schaal \(2020\)](#) and [Gallen and Winston \(2018\)](#) model endogenous infrastructure as the choice of a government or planner.<sup>7</sup> My framework is closer to [Felbermayr and Tarasov \(2019\)](#) and [Fajgelbaum and Schaal \(2020\)](#).<sup>8</sup> I contribute to this literature by providing the first test of the ability of a quantitative spatial model to explain changes in the infrastructure network exploiting an exogenous shock.<sup>9</sup> The use of a shock to fundamentals, such as the division of Germany, allows me to test the predictions of the model while controlling for time-invariant location-specific factors. This test of the model encourages the use of quantitative frameworks to study and quantify infrastructure upgrading decisions by governments.

The remainder of the paper is organised as follows. Section [II](#) describes the historical background of the division of Germany and the historical data sources. Section [III](#) develops a new spatial framework with endogenous infrastructure choice. Section [IV](#) explains the calibration of the model to the pre-division economy and tests the ability of the model to predict population, trade and highway construction. Finally, section [V](#) uses the calibrated model to quantify the importance of flexibility in the development of a transport infrastructure and section [VI](#) concludes.

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<sup>7</sup>[Allen and Arkolakis \(2019\)](#) allow for the emergence of endogenous trade costs due to decentralised shipping choices of traders along the network.

<sup>8</sup>[Gallen and Winston \(2018\)](#) investigate the choice of infrastructure in a general equilibrium model where infrastructure is a capital investment good that benefits all firms, without geographical differences.

<sup>9</sup>[Redding and Sturm \(2008\)](#) use the same historical episode as a shock to market access, to study the effects on city growth.

## II HISTORICAL BACKGROUND AND DATA

### A THE DIVISION OF GERMANY IN 1949

In the aftermath of the Second World War the territory of Germany became divided into four parts, represented in figure I. The two central parts (enclosing nowadays Germany) were occupied by foreign powers. The United States, Great Britain and France took control of the western part while the Soviet Union took control of the eastern part. The remaining areas, the most eastern territories, were annexed to Poland and Soviet Union. Following the deterioration of the political relations between the Western allies and the Soviet Union, with the onset of the Cold War, the two zones of occupation crystallised into two independent countries, West Germany and East Germany, in 1949.<sup>10</sup>

West Germany was the largest territory with 53% of the former German territory and 58% of the population (40 million in 1939).<sup>11</sup> East Germany contained around 23% of the area and 22 % of the population. The former German capital, Berlin, was located within East Germany and was also divided into West and East Berlin. It was the largest city in Germany, with 4 million inhabitants in 1939.

In the initial years after the division, in 1949, some economic and political ties between the two states persisted. Yet, the border became sealed from the eastern side in 1952 to prevent migrations to West Germany and all trade relations halted soon after. With the construction of the Berlin Wall in 1961, all population mobility between East and West Germany stopped as well. The division of Germany was recognised by the international community and was generally believed to be permanent.<sup>12</sup>

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<sup>10</sup>The delimitation of East and West Germany followed some pre-existing pattern mostly characterised by features of natural geography (Wolf, 2009).

<sup>11</sup>All numerical figures in this section are taken from Redding and Sturm (2008), and come from the 1952 edition of the Bundesrepublik statistical yearbook.

<sup>12</sup>The two German states became UN members in 1972, the perceptions of the West German population was that reunification was very unlikely even in 1980 (Gerhard Herdegen, 1992)

The division of Germany separated two territories that had been integrated for centuries. The foundation of the German Empire in 1871 was the culmination of decades of varying levels of economic and political integration. According to [Wolf \(2009\)](#), the economic integration within Germany improved substantially after the First World War and the German territories were an economically well-integrated area by 1933. The division, therefore, constituted an important shock that stopped all movement of people and goods between the two states and changed the geographic configuration of West Germany.

Regarding the transportation network, the former German Empire was well connected thanks to a railway system completed by the 1910s. This was the main mode of transportation in the XIXth century. After the First World War, the construction of a highway network was discussed in the German parliament but was finally rejected.<sup>13</sup> The ascent to power of Hitler marked the beginning of the construction of a German-wide highway network that became one of the star policies of the Nazi party. This massive infrastructure project was intended as a way to decrease unemployment and to gain attention from the International press. Fritz Todt, appointed by Hitler as the Inspector General of German Road Construction, traced a plan for the Highway network in 1934 heavily inspired by the previous plans designed in the 1920s and 1930s.<sup>14</sup>

Transit grew fast along the new highways. In 1955 short-distance shipments by truck were already three times larger than shipments by railway while long-distance truck shipments amounted to one-third of railway shipments (Figure [D.1](#) and table [D.1](#) in the Appendix).<sup>15</sup> By 1970, highways were already very popular, with short-distance shipments by truck being five times larger than short-distance shipments by rail and long-distance truck shipments approaching the magnitude of long-distance shipments by rail, and overtaking rail shipments by 1985.

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<sup>13</sup>In the 1920s German politicians discussed the construction of a modern highway system. They formed the HAFRABA association that lobbied for the construction of a restricted access motorway connecting Hamburg-Frankfurt-Basel and other connections between major cities ([Zeller and Dunlap, 2010](#)).

<sup>14</sup>[Schütz and Gruber \(1996\)](#), pp. 29-31, 35; also pp. 14–15, quote Heinrich Brüning in his memoirs concerning the Nazi government “taking the plans that we had prepared out of [a] drawer”.

<sup>15</sup>The data source is the Statistical Yearbook of the Bundesrepublik, multiple years.

## B RESHAPING OF THE HIGHWAY NETWORK AFTER DIVISION

I will now document the development of the German network of highways. As briefly mentioned, Hitler commissioned the design of a Highway network plan with the aim of giving Germany a modern transport system. Todt, appointed by Hitler as the Inspector General of German Road Construction, created the 1934 Highway Plan inspired by previous proposals, specially a highway plan designed in 1930. The 1930 Highway plan, proposed by the HAFRABA foundation, was designed with the aim of propelling the construction of a highway network in Germany following the Italian example.<sup>16</sup> Figure D.2 in the Appendix reproduces its outline. After Hitler's ascent to power, Todt modified this 1930 plan and proposed a new 1934 Highway Plan, that was approved by the Hitler administration. This outline is reproduced in Figure D.3. Both outlines are very similar, but the 1934 Plan is slightly denser and more East-oriented. The 1934 Highway plan had a total length of over 6,000 kilometres and extended across the whole German territory.

Highway construction moved swiftly: half of the 6,000 planned kilometres were built between 1934 and 1942, when construction stopped due to the worsening war situation.<sup>17</sup> Construction resumed after the war and an additional 3,000 kilometres had been completed by the year 1974. Figure D.5 in the appendix shows the planned and built kilometres by decade. In this paper, I focus on highway construction until the mid-1970s to make sure that I don't capture the eastern-oriented policies of West Germany in the late 1970s and 1980s. In addition, by the year 1974 the length of the highway network was just above the length of the 1934 Plan, which allows for a direct comparison.

Figure II shows the 1934 Plan outline and the actual highway network as it was by 1974. As we can see, the two networks look very similar. However, there are some differences. Several highways designed to cross the inner German border were actually never completed. And we see more highways near the western border in 1974 than in the 1934 Plan.

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<sup>16</sup>Zeller and Dunlap (2010), p. 48: "The chief model and stimulus for German lobby groups were the *autostrade* in Italy".

<sup>17</sup>Kunze and R. (1982), p. 31.

[FIGURE II]

To document whether this additional 3,000 kilometres were built following the prewar highway Plan, I classify the old and newly constructed highways into investments that were planned and investments that were reshaped (allocated to a different district). This classification is presented in table I. Until 1950, highway construction followed the prewar Plan (95% of kilometres built follow the Plan). However, I find considerable reshaping after the division: only 47.2% of the kilometres built between 1950 and 1974 followed the Plan while 52.8 % of the kilometres deviate from the prewar planned allocation.

[TABLE I]

This decomposition shows that the highway network in 1974 was considerably reshaped compared to the original prewar highway Plan. In the next section, I build a multi-region spatial trade model with endogenous infrastructure investments to analyse the sources of these deviations, and to quantify to what extent they can be explained by the division of Germany.

## C HISTORICAL DATA SOURCES

In the remaining of this section, I explain the data sources that I use in the paper. In order to analyse how the division of Germany affected infrastructure investments I need two different sets of data. First, information related to the evolution of the highway network including the outline different highway plans. Second, information about economic outcomes that will serve to calibrate the model and test its predictions. The unit of observation throughout the analysis will be the district (*Kreise*).<sup>18</sup> This subsection provides an overall description of the data sources employed, further details can be found in section C of the Appendix.

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<sup>18</sup>There are 412 districts between East Germany and West Germany of which 313 districts are in West Germany. For the empirical results the 313 districts are merged according to Mikrocensus regions to account for metropolitan areas.

The first contribution of this paper will be to document the evolution of the West German highway network and the deviations of the network from the prewar highway Plan. To do this, I digitise and geo-reference the outline of the highway plans of the years 1930 and 1934 from historical documents and compute the planned highway kilometres in each district. In addition, I collect and geo-reference highway construction data for East Germany and West Germany for the years 1938, 1950, 1965, 1974, 1980 and 1989 from historical maps and road atlases; and from 1950 and 1965 for federal roads. This allows me to document the length and pattern of the network by decade and by district. Figure D.4 and figure D.5 in the Appendix show the evolution of the network between these years and the pace of construction of the highway network by decade, in kilometres. Finally, I use the EuroGlobal maps dataset, available online, as a source for geo-referenced data of local roads in order to complete the German road network.

To calibrate the theoretical model and test its validity I also require information on historical economic outcomes. I use population data available by decade since 1938 at the district level (*Kreise*) from the historical census. In addition to population data, I collect and digitise new data of traffic of goods by road before and after division. For the pre-division period, I collect traffic of goods by road for eighteen aggregated traffic districts in Germany in the year 1939. The traffic data is collected in tons and reported in an aggregated way, as total shipments and total reception of goods by traffic district. For the post-division period, I digitise data on bilateral shipments of goods by road across West-German states, for the years 1966 and 1989.<sup>19</sup>

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<sup>19</sup>The choice of year is due to data availability constraints

### III A SPATIAL MODEL WITH ENDOGENOUS INFRASTRUCTURE

#### A MODEL SET-UP

In this section, I outline a spatial trade model with endogenous transport infrastructure.<sup>20</sup> I first explore the spatial equilibrium of the model given an initial infrastructure network. Next, I introduce a government that chooses how to upgrade the infrastructure network to maximise aggregate welfare. The solution of the model characterises the efficient infrastructure investment pattern, defined as the upgrade in the infrastructure network that maximises aggregate welfare. Finally, I use the model to derive qualitative predictions about the response of infrastructure to a shock such as the division of Germany in 1949.

The framework features different locations connected by the transport network. In each location there will be a number of local firms that produce an endogenous measure of differentiated varieties like in [Krugman \(1980\)](#). These varieties can be traded across space subject to transport costs. Workers move across locations to maximise their expected utility that depends on real income and heterogeneous preferences for locations. The model builds on the family of quantitative spatial models reviewed by [Redding and Rossi-Hansberg \(2017\)](#) and is specially close to [Redding \(2016\)](#). My contribution with respect to this framework is to model a benevolent government that chooses infrastructure investments (i.e. the quality of infrastructure) to maximise aggregate welfare.

#### B PREFERENCES

The model features many locations, indexed by  $i, n \in N$  connected by the transport network. Locations differ in their position in the network, their land endowments,  $H_n$ , and their exogenous labour productivity,  $A_n$ . There is a measure  $L$  of workers in the economy. Workers derive utility from the consumption of differentiated varieties of the tradable good, from the consumption of

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<sup>20</sup>A detailed exposition of the theoretical framework is contained in section [A](#) of the Appendix.

housing and from the location they choose to live in. In particular, utility for worker  $\omega$  is given by:

$$U_n(\omega) = b_n(\omega) \left( \frac{C_n(\omega)}{\alpha} \right)^\alpha \left( \frac{H_n(\omega)}{1-\alpha} \right)^{1-\alpha}. \quad (1)$$

Workers spend a fraction  $\alpha$  of their income on the goods consumption bundle,  $C_n$ , that is defined over the endogenously-determined measure of differentiated varieties ( $z$ ) supplied in each location  $i$ ,  $M_i$ , given by  $C_n = \left[ \sum_i^N \int_0^{M_i} c_{ni}(z)^{\frac{\sigma-1}{\sigma}} dz \right]^{\frac{\sigma}{(\sigma-1)}}$ , where  $\sigma > 1$  is the elasticity of substitution across varieties. The remaining income share  $(1-\alpha)$  is spent on housing. Finally, workers have heterogenous preferences across different locations, modelled as an idiosyncratic taste component  $b_n$ . Worker  $\omega$  draws a vector of  $N$  realisations  $\{b(\omega)_n\}_{n=1\dots N}$  from a Fréchet distribution with shape parameter  $\epsilon$ , that governs the dispersion of preferences across workers for different locations.<sup>21</sup>

## C PRODUCTION, TRADE AND PRICE INDEX

Production of the differentiated varieties takes place under monopolistic competition, following [Krugman \(1980\)](#). To produce a variety  $z$  in location  $i$ , firms are required to pay a fixed cost of  $F$  units of labour together with variable production costs that depend on the productivity of the region,  $A_i$ . Thus, the labour requirements to produce  $q_i(z)$  units of variety  $z$  are  $l_i(z) = F + \frac{q_i(z)}{A_i}$ . Because of this fixed cost, each firm produces a single differentiated variety in equilibrium. Firms maximise profits by charging a production price for a variety produced in region  $i$  equal to a constant mark-up over the marginal cost of production,

$$p_i(z) = \left( \frac{\sigma}{\sigma-1} \right) \frac{w_i}{A_i}. \quad (2)$$

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<sup>21</sup>The parameter  $\epsilon$  governs the dispersion of heterogenous preferences across workers. A large  $\epsilon$  implies a low dispersion of the distribution (low standard deviation). Thus, the idiosyncratic preferences are more similar across locations for all workers. Workers have resembling tastes so they react more strongly to changes in real incomes. On the contrary, when  $\epsilon$  is small the dispersion in preferences is large, and workers are very heterogenous in their taste.



The free entry condition drives profits down to zero and pins down the scale of production of each firm to  $y_i = A_i(\sigma - 1)F$ . As we can see more productive locations will have larger firms because they will be able to cover the fixed cost more easily. Given the scale of each firm and the local labour supply, the labour market clearing condition pins down the number of varieties (equal to the number of firms) in each region:  $M_i = L_i/(\sigma F)$ .

Workers in any region will consume both local and non-local varieties, as determined by the CES demand structure of preferences. Since varieties produced in the same region will have the same price, we can use the number of varieties in each region to write the demand for varieties produced in  $i$  consumed by region  $n$  as:

$$X_{n,i} = \frac{L_i}{\sigma F} \frac{p_{n,i}^{1-\sigma}}{P_n^{1-\sigma}} \alpha X_n, \quad (3)$$

where  $p_{n,i} = p_i T_{n,i}$  is the price at destination of a variety produced in  $i$  and consumed in  $n$ , that includes transport costs,  $T_{n,i}$ . The transport technology will be defined below. Finally,  $P_n^{1-\sigma} = \left(\frac{\sigma}{1-\sigma}\right)^{1-\sigma} \left(\frac{1}{\sigma F}\right) (\sum_k L_k p_{n,k}^{1-\sigma})$  is the consumption goods price index in location  $n$  and  $X_n$  is expenditure in location  $n$ .

## D RESIDENTIAL CHOICE AND INCOME

**Workers' residential choice** Workers choose where to live by maximising indirect utility, given by real income and the idiosyncratic preference taste. The distribution of indirect utility is also Fréchet and, given the properties of this probability distribution, we can write the share of workers that choose to live in location  $n$  as:

$$\frac{L_n}{L} = \frac{(v_n / P_n^\alpha r_n^{1-\alpha})^\epsilon}{\sum_{k=1}^N (v_k / P_k^\alpha r_k^{1-\alpha})^\epsilon}, \quad (4)$$

where  $v_n$  denotes income in location  $n$  and differs from wage because land rents are redistributed back to residents as explained below. Given the specification of preferences, we can write the indirect utility function of worker  $\omega$  in location  $n$  as:

$$U_{n,\omega} = \frac{b_n(\omega)w_n}{P_n^\alpha r_n^{1-\alpha}}. \quad (5)$$

Expected utility for a worker across locations is given by:<sup>22</sup>

$$\tilde{U} = E(U_{n,\omega}) = \delta \left[ \sum_{n=1}^N (v_n / P_n^\alpha r_n^{1-\alpha})^\epsilon \right]^{1/\epsilon}, \quad (6)$$

where  $\delta = \Gamma\left(\frac{\epsilon}{\epsilon-1}\right)$  and  $\Gamma(\cdot)$  is the gamma function. We impose  $\epsilon > 1$  to ensure a finite value of the expected utility. Because indirect utility follows a Fréchet distribution, the expected utility conditional on living in location  $n$  is the same across all locations and equal to the expected utility of the economy as a whole.<sup>23</sup> Following Redding (2016), I use this measure of expected utility as a proxy for aggregate welfare.

**Income** Residential land is assumed to be in fixed supply, as a function of land endowments. I denote the endowment of residential land in location  $n$  by  $H_n$ , that can be used for housing. Each agent spends  $(1 - \alpha)$  share of her income on renting residential land and expenditure on land in each location is redistributed lump-sum to the workers residing in that location as in Redding (2016). This implies that total income in location  $n$ , denoted by  $v_n L_n$ , will equal total labour income plus expenditure on residential land:  $v_n L_n = w_n L_n + (1 - \alpha)v_n L_n = (w_n L_n)/\alpha$ . This assumption minimises the effects of introducing a housing market in the model while still allowing for a dispersion force that motivates workers to spread across locations because they dislike paying high rents. The land market clearing condition will pin down the equilibrium land rent,  $r_n$ , in each location.

<sup>22</sup>See part A of the appendix for derivation details

<sup>23</sup>Because more productive locations attract more workers despite their preference taste the expected value of indirect utility,  $E(b_n(\omega)w_n / P_n^\alpha r_n^{1-\alpha})$  will equalise across locations.

## E GEOGRAPHY, INFRASTRUCTURE AND TRANSPORT COSTS

**Geography** The geography of the model is a plane of generic shape. Each of the  $i, n \in N$  locations is situated in a delimited region of the plane, of potentially different extension, such that each region contains exactly one location. Locations are assumed to be a point in the centre of the region where consumption and production happen. Each location is connected to its neighbouring locations by the transport network.

The transport network is a simple undirected graph composed by a set of vertices  $V$  that are connected by a set of edges  $E$ . Only neighbouring vertices are connected by edges, and the subset of edges  $E$  is defined as:  $E \subseteq \{\{x, y\} | y \in N(x) \text{ and } x, y \in V \text{ and } x \neq y\}$ , where  $N(x)$  denotes the neighbourhood of vertex  $x$ . A different number of closest neighbours may be chosen to belong to the neighbourhood of  $x$ .<sup>24</sup> The length of  $E$  is  $\mathcal{L}=|E|$ , and I index it by  $\ell = 1, \dots, \mathcal{L}$ . As explained above, these network edges (links) can be transited freely by workers but moving goods is costly.<sup>25</sup>

The set of locations  $N$  is contained in  $V$ , forming part of the vertices of the network, but there may be additional vertices that are not habitable.<sup>26</sup> Finally, the set  $N$  in this model is fixed, so there is no city creation or destruction, and the sets  $V$  and  $E$  are also assumed to be fixed.<sup>27</sup>

Figure III represents an example of this type of geography with 9 locations. All vertices in the graph are locations,  $V=N$ , and vertices are only connected to their four closest neighbours, so that  $E$  is a subset of all possible edges between the nine graph vertices. There are 12 edges,  $\mathcal{L} = 12$ . The cost of moving along the edges of the network, on the contrary, can be improved by investing in infrastructure.

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<sup>24</sup>In the calibration of the model the connexion to adjacent locations will be given by the existing local roads and federal roads (Bundesstrasse)

<sup>25</sup>I abstract from migration costs in the interest of simplicity but mobility frictions could be included in a model extension. However, previous work has found that aggregate welfare gains from transport infrastructure upgrades mostly come from changes in the movement of goods rather than from reduced migration costs (Morten and Oliveira, 2018).

<sup>26</sup>This assumption is needed to have a dense enough network while keeping the number of locations relatively small.

<sup>27</sup>The assumption of a fixed network of links that can be upgraded in terms of quality is also present in related papers in the literature. This constitutes an important difference with the literature about banking, social and business networks where the links are endogenous. Allen and Arkolakis (2014), on the contrary, consider the continuum of space as the domain for the transport cost function that is defined at every point of the plane (instantaneous trade costs). The existence of transport network changes the cost of transit over specific points on the plane.

[FIGURE III]

**Shipping costs** Investments in infrastructure are made at the level of the location and on the intensive margin. Location-level investments mean that the government will choose how much to invest in each location. Investments in a given location will upgrade all the links (edges) contained in the region of that location, rather than on a given link.<sup>28</sup> The vector of government investments,  $\Phi$ , has length  $N$ , and will be composed of location-specific investments,  $\{\phi_n\}$ , for each  $n$ . This simplifying assumption allows me to capture the complementarities of infrastructure investments over space in a simple way, although the more general link-level perspective could be adopted in an extension of the model. Assuming that investments happen on the intensive margin implies that the government cannot create new infrastructure links but can change the cost (for example speed) at which links are transited.

In this economy, a variety produced in region  $i$  but consumed in  $n$  will have a price  $p_{n,i} = p_i T_{n,i}$ , that includes a transport cost,  $T_{n,i}$ . I will now define how the matrix of transport costs  $\{T\}$  is determined.

The cost of shipping along an edge  $(x, y)$ , where  $x$  and  $y$  are adjacent by assumption, will be a function of distance  $d_{x,y}$ , which is exogenously given by geography, and the quality of infrastructure along that edge that will determine how costly (slowly) can this distance be transited. The way in which the quality of infrastructure affects the shipping costs is defined by the ad-valorem cost of shipping across edge  $(x, y)$ :

$$w(x, y) = \frac{1}{2} \left( \frac{d_{x,y}}{\phi_{r(x)}^\gamma} + \frac{d_{x,y}}{\phi_{r(y)}^\gamma} \right), \quad (7)$$

where  $r(x)$  indicates the region in which vertex  $x$  is contained, and therefore, the quality of infrastructure in  $x$ .<sup>29</sup> This shipping function is just an average of the cost of shipping along two

<sup>28</sup>In the real world a location may have one very high-quality highway and one very low-quality road. Therefore, we may think of  $\phi_i$  as the average quality of the infrastructure stock in location  $i$ .

<sup>29</sup>Notice that if all vertices are locations,  $N=V$ , then  $r(x)=x$ . But more generally, there may be vertices in the graph that do not correspond to a habitable location.

different levels of infrastructure quality  $\{\phi_{r(x)}, \phi_{r(y)}\}$ . This specification of transit costs means that  $w_{x,y}$  units of the good shipped will be paid in order to ship one unit of any good across link  $(x, y)$ . As we can see, a higher infrastructure investment will reduce the ad-valorem cost of shipping. I assume that  $\phi_{r(i)} \geq 1$ , for all locations so that the transport cost will always be bounded by the physical geography, meaning that infrastructure investments cannot increase the shipping costs. Parameter  $\gamma$  is the returns to infrastructure investments. It measures the elasticity of the ad-valorem transit cost to infrastructure investments. I assume it to be positive, so that the cost of transit is decreasing on infrastructure investments. It determines whether infrastructure has increasing returns ( $\gamma > 1$ ) or decreasing returns ( $\gamma < 1$ ).

**Transport costs:** Given the shipping costs along all edges (adjacent links), what is the transport cost between location  $n$  and non-adjacent location  $i$ ? In this network economy there will be many alternative paths to ship a good between non-neighbouring locations. In the network represented by figure III, there are different paths by which you can ship goods between location 3, on the top-right corner, and location 9, on the bottom-right corner. I assume that transport costs are defined by the least-cost path, and linear in the ad-valorem cost of distance.<sup>30</sup> Assuming that infrastructure quality is homogeneous across locations in figure III, the ad-valorem transport cost between locations 3 and 6 is:  $T_{3,6} = 1 + w(3, 6)$

I assume that ad-valorem transport costs are linear in distance and model the ad-valorem transport cost between locations (3) and (9) as given by:

$$T_{3,9} = 1 + w(3, 6) + w(6, 9), \quad (8)$$

since transiting location (6) is the shortest path to get from (3) to (9). More generally, the transport cost matrix will be the collection of bilateral transport costs along the least-cost path between each

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<sup>30</sup>I model transport costs as linearly increasing in the distance component to avoid that the number of transited locations affects the total cost. In multiplicative functions of ad-valorem costs, the number of locations increases transport costs and paths that cross less locations are mechanically cheaper.

location pair.<sup>31</sup> In standard trade models direct shipping is assumed, implying that the cost of shipping between any origin and any destination only depends on origin and destination-specific parameters. This is not the case in the transport function I assume, since investments in a region can potentially affect the whole matrix of transport costs.

To represent the cost-minimising combination of paths that connects all locations, I define a least-cost path vector for each location-pair. Each of these vectors has a length equal to the total number of edges in the network,  $\mathcal{L} = |E|$ . The elements of the vector indicate whether an edge  $(x, y)$  is included in the path that connects a given location-pair along the cost-minimising route. It is related to the *transition matrix* in the network literature as it indicates how to transition from one vertex of the network to any other. For location-pair  $n$  and  $i$ , the element  $\mathbb{I}_{n,i}^{x,y} \in \mathbb{I}_{n,i}$  indicates whether link  $(x, y)$  is on the least-cost path when shipping goods from location  $n$  to location  $i$  and is defined as:

$$\mathbb{I}_{n,i}^{x,y} = \begin{cases} 1, & \text{if } (x, y) \text{ is in the least-cost path between } n \text{ and } i \\ 0, & \text{if } (x, y) \text{ is not in the least-cost path between } n \text{ and } i. \end{cases} \quad (9)$$

We can now define the transport cost between any two locations  $n$  and  $i$ ,  $T_{n,i}$ , as

$$T_{n,m} = 1 + \sum_{\mathcal{L}} \mathbb{I}_{n,i}^{x,y} w(x, y), \quad (10)$$

where  $\mathcal{L}$  is the index set by which we have indexed the set of edges,  $E$ . The transport cost between  $n$  and  $i$  is simply the sum of the ad-valorem distance-related costs, scaled by the infrastructure quality of all the locations that are transited along the least-cost path. This function is nested in the more generic transport costs formulation of [Allen and Arkolakis \(2019\)](#), when we assume there is not difference across traders and all choose to ship along the least-cost path.<sup>32</sup>

<sup>31</sup>This is similar to modelling a shadow transport sector that operates under perfect competition, and therefore, ships goods at the minimum costs.

<sup>32</sup>Given that we have defined  $\{\mathbb{I}_{n,i}^{x,y}\}$  as the least-cost path vector this implies that we can also express the transport friction between  $n$  and  $i$  as  $T_{n,i} = \min_k (T(P_{n,i}^k))$  where  $T(P_{n,i}^k)$  is the transport cost of shipping a good from  $n$  to  $i$  along path  $k$  over the set of possible paths that lead from  $n$  to  $i$ .

Notice that the least-cost path indicator  $\{\mathbb{I}_{n,i}^{x,y}\}$  will take value 1 more often for more central edges. This is because edges located in the centre of the geography will be along the path of most trade flows while edges located in the margins of the geography will almost never be transited by trade flows between other locations. Changes in the infrastructure quality will lead to changes in the least-cost path vectors and affect the full matrix of transport costs.

Finally, I adopt a normalisation common to all trade models by assuming  $T_{n,n} = 1$ , equivalent to assuming free intra-location trade and normalising the cost of trading out of the location by the internal shipping cost.

## F GENERAL EQUILIBRIUM

**Spatial equilibrium** For a given geography, infrastructure quality vector and shortest-path vector indicator,  $\{d, \Phi, \{I_{n,i}\}_{\forall i,n}\}$ , and exogenous land endowments  $\{H_n\}_{\forall n \in N}$  and productivities  $\{A_n\}_{\forall n \in N}$ , the spatial equilibrium is a combination of wages, price indices, rents and labour allocations,  $\{w_n, P_n, r_n, L_n\}$  such that the goods and housing markets clear in each location, the domestic labour market clears domestically and expected utility is equalised across all regions.<sup>33</sup> The following equations define the equilibrium vector  $\{w_n, P_n, r_n, L_n\}$ :

The goods market clearing is given by the balanced trade condition:

$$w_n L_n = \sum_i \frac{L_i}{\sigma F} \left( \frac{\sigma}{\sigma - 1} \frac{w_i}{A_i} T_{n,i} \right)^{1-\sigma} (P_i)^{\sigma-1} w_i L_i, \forall i, n. \quad (11)$$

The Price index in location  $i$  given by:

$$P_n^{1-\sigma} = \sum_i \frac{L_i}{\sigma F} \left( \frac{\sigma}{\sigma - 1} \frac{w_i}{A_i} T_{n,i} \right)^{1-\sigma}, \forall i, n. \quad (12)$$

The rental rate is given by the clearing of the housing markets:

$$r_n = \left( \frac{1 - \alpha}{\alpha} \right) \frac{w_n L_n}{H_n}, \forall n. \quad (13)$$

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<sup>33</sup>Previous work by [Allen and Arkolakis \(2014\)](#) and [Redding \(2016\)](#) has proved that under quasi-symmetric transport costs, the equilibrium conditions can be rewritten as a system of  $N$  equations in terms of the residential population vector, model parameters and aggregate utility. Once equilibrium population  $\{L_n\}$  is computed, the equilibrium vector of prices,  $\{w_n, P_n, r_n\}$ , can be solved for using the market clearing conditions.

The fraction of workers that chooses to live in location  $n$  is given by the workers' residential choice equation:

$$\frac{L_n}{L} = \frac{(v_n/P_n^\alpha r_n^{1-\alpha})^\epsilon}{\sum_{i=1}^N (v_i/P_i^\alpha r_i^{1-\alpha})^\epsilon} \forall i, n. \quad (14)$$

Equations (11), (12), (13) and (14) can be solved for the equilibrium vector  $\{w_n, P_n, r_n, L_n\}$ . Lastly, the equilibrium level of expected utility,  $\tilde{U}$ , is implicitly determined by the domestic labour market clearing,  $\sum_i L_n = L$ .

**Existence and Uniqueness** The structure of the spatial equilibrium in this model belongs to a family of quantitative models widely used in the fields of International Trade (Allen and Arkolakis, 2014) and urban economics (Redding and Rossi-Hansberg, 2017). In particular, Allen and Arkolakis (2014) show that given the land endowment, productivity and amenity parameters and quasi-symmetric bilateral trade frictions, there exists a unique and stable spatial equilibrium for a specific configuration of the model's parameters (Theorems 1 and 2, (Allen and Arkolakis, 2014)).<sup>34</sup>

The intuition behind the uniqueness and stability condition can be clearly explained in terms of the production and amenity externalities in the model. Denote by  $\lambda$  the production externality, that in the monopolistic competition set-up arises from the fact that the number of varieties produced in a location is proportional to its population, creating an agglomeration externality. Second, define by  $\eta$  the amenity externality, that will be negative in this model and arises from two sources: the inelastic supply of land that is rented by workers creating congestion, and the heterogeneity in workers' preferences that makes labour less elastic to changes in real income across locations. Given the land area, productivity and amenity parameters and quasi-symmetric bilateral trade frictions, there exists an equilibrium that is unique and stable if  $\lambda + \eta \leq 0$ .<sup>35</sup> Thus, there is a unique stable equilibrium as long as dispersion forces are at least as strong as agglomeration forces. As shown in Redding

<sup>34</sup>The transport costs defined above are symmetric and thus, I can apply the results in Allen and Arkolakis (2014).

<sup>35</sup>Using the same notation as Allen and Arkolakis (2014), this condition is equal to  $\alpha + \beta \leq 0$  which ensures that  $\gamma_2/\gamma_1 \in [-1, 1]$ . In my setting,  $\gamma_1 = \sigma(\frac{1}{\alpha\epsilon} + \frac{(1-\alpha)}{\alpha})$  and  $\gamma_2 = 1 + \frac{\sigma}{\sigma-1} - (\sigma-1)(\frac{1}{\alpha\epsilon} + \frac{(1-\alpha)}{\alpha})$ .



(2016), this condition can be rewritten in terms of the parameters of this model as:

$$\left( \frac{1}{\sigma - 1} - \frac{1}{\alpha \epsilon} - \frac{(1 - \alpha)}{\alpha} \right) \leq 0, \quad (15)$$

where  $\lambda = \frac{1}{\sigma - 1}$  and  $\eta = -\frac{1}{\alpha \epsilon} - \frac{(1 - \alpha)}{\alpha}$ . In section A in the Appendix, I use the result in Redding (2016) to write the welfare in a location as a function of the parameters and labour force in that location. The elasticity of a location's welfare to its population is  $-(\frac{1}{\epsilon} + (1 - \alpha) - \frac{\alpha}{\sigma - 1})$ , which is just a reformulation of the above condition.

This condition is fulfilled given the calibration of parameters that I will present in the next section.

## G PROBLEM OF THE GOVERNMENT: CHOICE OF INFRASTRUCTURE INVESTMENT

I model the choice of infrastructure as a Stackelberg game between the Government and the economic agents in the economy (workers and firms). The Government is the leader and thus has the advantage to choose first in the game that is solved by backward induction. The Government chooses infrastructure to maximise expected utility,  $\tilde{U}$ , constrained by the choices of workers and firms, given by the decentralised equilibrium allocation. This set-up is similar to a Ramsey problem with a Government that maximises welfare replacing the FOCs from the problems of consumers, firms and workers into the constraints.

I assume that the Government can choose how to allocate a fixed amount of resources to improve infrastructure across all the locations in the economy. This budget, that I denote by  $Z$ , is modelled as an endowment of the government and thus, is assumed to be exogenous. The cost of investing in location  $n$  is  $c_n \phi_n$  and the budget constraint of the government is:

$$\sum_n c_n \phi_n \leq Z. \quad (16)$$

The marginal cost of construction is equal to  $c_n$ , that is allowed to differ across locations.

**Government's problem** We can write the problem of the Government as follows:

$$\text{Max}_{\{\phi_n\}} \delta \left[ \sum_{n=1}^N (v_n / P_n^\alpha r_n^{1-\alpha})^\epsilon \right]^{1/\epsilon},$$

subject to:

1. *Goods market clearing*

$$w_n L_n = \sum_i \frac{L_n}{\sigma F} \left( \frac{\sigma}{\sigma-1} \frac{w_n}{A_n} T_{n,i}(\Phi) \right)^{1-\sigma} P_i^{\sigma-1} w_i L_i, \forall i, n. \quad (18)$$

2. *Labour market clearing*

$$\frac{L_n}{L} = \frac{(w_n / P_n^\alpha r_n^{1-\alpha})^\epsilon}{\sum_{i=1}^N (w_i / P_i^\alpha r_i^{1-\alpha})^\epsilon} \text{ and } \sum_i L_i = \bar{L}, \forall i, n. \quad (19)$$

3. *Least-cost path shipping*

$$\text{argmin } T_{n,i}(\Phi) = \{\mathbb{I}_{n,i}\}, \forall i, n. \quad (20)$$

4. *Government's budget constraint*

$$\sum_n c_n \phi_n \leq Z, \quad (21)$$

where  $P_i = \left[ \sum_\ell^N \frac{L_\ell}{\sigma F} \left( \frac{\sigma}{\sigma-1} \frac{w_\ell}{A_\ell} T_{\ell,i} \right)^{1-\sigma} \right]^{1/(1-\sigma)}$ ,  $r_n = \left( \frac{1-\alpha}{\alpha} \right) \frac{w_n L_n}{H_n}$  and  $\delta = \Gamma(\frac{\epsilon}{\epsilon-1})$ , where  $\Gamma$  is the gamma function.

**Intuition for infrastructure investment allocation** To build some intuition about the allocation of infrastructure by the government, I write the Lagrangian associated with the government's problem and derive the first order condition with respect to  $\phi_k$  (see part A of the Appendix for

details). In the interest of clarity, let us consider the same problem but without allowing the vector of least-cost paths to change and in a model with no housing ( $\alpha = 1$ ). This assumption avoids a change in the optimal shipping path to a change in infrastructure upgrading and abstracts from the response of rents to new investments.<sup>36</sup> Holding the shipping path between every pair of locations constant, the first order condition with respect to  $\phi_k$  is:

$$\frac{\partial \mathcal{L}}{\partial \phi_k} = 0 : C \underbrace{\left[ \sum_n U_n^{(\epsilon-1)} \frac{\partial U_n}{\partial \phi_k} \right]}_{\text{Direct effect}} + \underbrace{\sum_n \sum_i \eta_n \frac{\partial X_{n,i}}{\partial \phi_k}}_{\text{Response of wages}} + \underbrace{\sum_n \lambda_n \frac{\partial (L_n/L)}{\partial \phi_k}}_{\text{Response of Labour}} = \underbrace{\mu c}_{\text{Marginal cost}}, \quad (22)$$

where  $C = \delta \left[ \sum_n U_n^\epsilon \right]^{\frac{1}{\epsilon}-1}$  is constant across all locations. Equation (22) shows that infrastructure investment is chosen so that the marginal benefit of investing in a location, left-hand side of the equation, equates the marginal cost of building infrastructure in that location. The marginal benefit is composed of a direct effect, coming from increased utility of consumers that enjoy lower product prices due to the reduction in transport frictions, and of an indirect effect coming from the response of wages and workers. As we can see, the direct effect is just the partial equilibrium effect of an upgrade of infrastructure on aggregate welfare, before the adjustment of wages and population.

We can build intuition about how the efficient infrastructure in location  $k$  depends crucially on the transport network by approximating infrastructure investment in location  $k$  with the *partial equilibrium* term. Let us define function  $e(j, j') = \left[ \frac{U_j^{\epsilon-1}}{P_j} \frac{X_{j,j'}}{T_{j,j'}} \right]$ , that is increasing in the expenditure of location  $j$  in products of location  $j'$ . Manipulating equation (22) we can write infrastructure investment level in location  $k$  as:

$$\phi_k^{\gamma+1} = \frac{\gamma}{\mu c} C \left( \underbrace{\sum_n e(n, k) \sum_{x \in N(k)} \mathbb{I}_{n,i}^{x,k} d_{x,k}}_{\text{Exports of } k} + \underbrace{\sum_{n \neq k} \sum_{i \neq k} e(n, i) \sum_x \mathbb{I}_{n,i}^{x,k} d_{x,k}}_{\text{Centrality of } k} \right). \quad (23)$$

<sup>36</sup>Allowing for changes in the shipping path would just add an additional term to the expression below, accounting for how the shipping path matrix will change after an infrastructure upgrading. This effect is not quantitatively very large.

Equation (23) shows that infrastructure investments in location  $k$  will increase with the importance of  $k$  as an exporter, first term in parenthesis, and with the centrality of  $k$  in the network, second term in the parenthesis.<sup>37</sup>

The first term is a sum across all locations of a function that increases in exports of  $k$ , weighted by size of the edge of the network in location  $k$ . Therefore, if location  $k$  is a large exporter, the gains from investing in infrastructure in  $k$  will increase. In this first term  $\mathbb{I}_{n,k}^{x,k} = 1$  for all  $n$  since it indicates whether the least-cost path from  $n$  to  $k$  transits the neighbourhood of  $k$ ,  $\mathcal{N}(k)$ .

The second term is a sum across all location pairs in the network that are different to  $k$ . Therefore, it shows that investing in region  $k$  also benefits trade flows with origin or destinations different from  $k$  but that transit the region. Which trade flows will matter? The ones for which  $\mathbb{I}_{n,i}^{x,k} = 1$ , in other words, the trade flows of regions for which location  $k$  is “on the way”, along the least-cost path. If location  $k$  is very remote in the network, vector  $\mathbb{I}_{n,i}^{x,k}$  will take value 0 for most pairs  $(i,n)$ . If location  $k$  is very central in the network, many of the trade flows will transit by it and  $\mathbb{I}_{n,i}^{x,k}$  will take value 1 for most pairs. As we can see, the second term will be large for central regions. This expression for  $\phi_k$ , abstract of general equilibrium effects, includes the gains for location  $k$ , first term, as well as the sum of the gains for all the locations that may benefit from the infrastructure upgrade in  $k$ , and is reminiscent of Samuelson’s condition for the allocation of public goods (Samuelson, 1954).

**Qualitative predictions of the model** The theoretical framework developed in this section helps us understand what is the efficient infrastructure pattern across regions in a general equilibrium framework. As indicated in equation (23), infrastructure quality will be higher in locations that are an important *source* of trade flows, and in locations that are *central* in terms of transit flows. In this framework, a permanent change in the size of trade flows or trade transit would create incentives to reshape the infrastructure network. Given some infrastructure budget, the new investments would be allocated to maximise aggregate welfare given the new fundamentals and the initial transport

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<sup>37</sup>Equation (23) is an implicit function of  $\phi_k$ , since  $e(j, j') = \left[ \frac{U_j^{e-1}}{P_j} \frac{X_{jj'}}{T_{jj'}} \right]$ , depends on infrastructure investments as well.

network.

The division of Germany into East Germany and West Germany in 1949 was a sharp shock to the German economic geography (Redding and Sturm, 2008). Firstly, it affected exports of West German districts to East Germany since all trade stopped. Besides, the transit of goods and the transport network changed once the inner border was established, causing previously central districts to become remote after division. These changes would predict that the districts most affected by the division, those that lost more trade and became less central, should have been allocated smaller infrastructure investments. These predictions are confirmed by the reshaping of the network that we observed in figure II. Highways planned near the inner German border were never built, while new unplanned highways appeared in the West and along the North-South axis.

## H SOLUTION ALGORITHM

As described above the government problem nests the transport problem (optimal shipping) and the spatial equilibrium problem. Since there is no congestion in shipping, the transport problem can be separated from the spatial equilibrium/allocation problem. This layered structure allows me to solve it sequentially. First, given the transport network (graph and investment levels in vector  $\Phi$ ), I solve for the matrix of transport costs using a least-cost path algorithm.<sup>38</sup> Second, given the parameters, fundamentals and matrix of transport costs, we can compute the spatial equilibrium and the aggregate welfare. As discussed above, given a specific parameter configuration, the spatial equilibrium exists, is unique and stable. Therefore, for a given transport network and a vector of infrastructure investments, we can easily solve for the aggregate welfare level using a simple iterative algorithm (Allen and Arkolakis, 2014).

Given this nested structure, I can rewrite the problem as an optimisation of the expected utility

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<sup>38</sup>I use Dijkstra's least-cost path algorithm to solve for the transport costs between all region-pairs

in equilibrium over the infrastructure investment vector:

$$\text{Max}_{\{\phi_j\}_{j \in N}} U^{eq} = f(w^{eq}(\Phi), P^{eq}(\Phi), r^{eq}(\Phi), L^{eq}(\Phi), T^{eq}(\Phi), \Phi), \quad (24)$$

where  $U^{eq}$  is the equilibrium expected utility for a given infrastructure network and a given vector of infrastructure investments ( $\Phi$ ). The equilibrium expected utility is a function of the equilibrium wages,  $w^{eq}(\Phi)$ , equilibrium Price indices  $P^{eq}(\Phi)$ , equilibrium rents,  $r^{eq}(\Phi)$ , equilibrium population allocation,  $L^{eq}(\Phi)$  and the equilibrium transport cost matrix,  $T^{eq}(\Phi)$ .

I use the following solution algorithm to find the optimal investment vector:

1. Start from investment vector  $\{\Phi_0\}$  where  $\phi_n$  is set to 1 for all  $n$ . This is the no-investment case, with shipping costs unchanged.
2. Solve for the transport costs matrix, spatial equilibrium and expected utility using an iterative procedure.
3. Use an interior-point algorithm to take utility-maximising step to get  $\{\Phi_1\}$ .
4. Go back to 2., and repeat until convergence to a local optimum.

Since the problem does not feature congestion and the government's problem is not globally convex, I cannot proof that the solution is the global optimum.<sup>39</sup> Given how the government problem has been defined, this does not need to be a major concern. The local optimum will be the best possible deviation from the initial network in the neighbourhood of the starting point. This solution coincides with the problem the government has to solve: how to continue the allocation of the remaining part of the planned network departing from the existing network. On the contrary, the solution of the global optimum may be very far from the initial network and require a much more significant

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<sup>39</sup>See [Fajgelbaum and Schaal \(2020\)](#) for a detailed discussion about convexity in spatial models with networks.

investment. Because of this, the solutions I find are heuristic and should be thought of as a lower bound of aggregate welfare relative to the global optimum.

In the next section, I take the model to historical data of Germany and I provide several tests of its ability to capture the economic geography of Germany.

## **IV CALIBRATION AND TEST OF THE MODEL**

In the previous section, I built a quantitative spatial model that incorporates endogenous infrastructure investments. In this section, I take the model to the data. The goal is to achieve a quantification of the model that captures highway choice in Germany, both before and after division, and that can be used to study the economic gains from infrastructure investments.

In the first part of this section, I explain the calibration strategy and the parametrisation of the model. In the second part of this section, I test the quantitative performance of the model.

### **A TAKING THE MODEL TO GERMANY BEFORE DIVISION**

The goal of this calibration is to obtain a quantitative model that represents as close as possible the spatial equilibrium of the German economy before the division. To take the model to the data I need to calibrate two sets of parameters: first, the pre-division transport network that will determine the initial transport cost matrix, and, second, the parameters of the model that will determine the spatial equilibrium. Table [D.3](#) in the Appendix provides a summary of all the parameter values.

#### ***A.1 Initial network and Transport costs***

The geography of this model is composed of a set of locations connected by the transport network, that can be represented as graph of vertices and edges. In the calibration, I think of the regions in

the model as the districts in Germany (*kreise*) and I choose one population centre in each district that will represent that region's location in the model.<sup>40</sup>

This graph represents the underlying geography of Germany and is assumed to be fixed. On the contrary, the quality of the links can be upgraded by investing in infrastructure. I build the underlying graph as follows. I combine the highways, (Autobahns) and all federal highways (Bundesstraße) that existed in 1938.<sup>41</sup> I add the local roads needed to ensure that all districts in Germany, represented by a population centre, are connected to the network. This gives me a network that contains all german districts.<sup>42</sup> Figure D.6 in the Appendix displays the roads chosen for the initial network and the graph corresponding to this network.<sup>43</sup> Table B.1 presents a summary of the size of the network in terms of edges, vertices and length.

After building the network, I compute the cost of transporting goods following [Combes and Lafourcade \(2005\)](#). The shipping cost is made up by a time-related component and a distance-related component, that vary with the type of road: highway, federal road (regional roads) and local roads. To compute the transport costs in 1938, I assume that all highways are federal roads in terms of costs because the highways that had been built by then were fairly disconnected from the network. Finally, I convert the initial shipping costs (in euros) to ad-valorem transport costs by scaling the cost of shipping by the average value of the shipment of a truck in Germany in 1950. Full details about the cost computation can be found in part B of the Appendix.

Given the graph and the ad-valorem shipping costs associated to each link in the network, I can compute the initial transport cost matrix by applying a least-cost path algorithm to the network. This calibration yields the transport cost matrix in 1938.

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<sup>40</sup>To select these nodes, I intersect the German network of highways, federal roads and local roads with each district's surface and select the most central point in the network, as explained in part B of the Appendix.

<sup>41</sup>The federal highways are roads with multiple lanes but not limited-access like Autobahns

<sup>42</sup>I provide further details of the construction of the network in B of the Appendix.

<sup>43</sup>For the network construction I use the Network Analysis toolkit in the geographic information software ArcGIS.



## A.2 Parameter choice

In addition to the transport cost matrix  $\{T_{i,n}\}$ , calculated as explained above, the model described in section III has several additional parameters to be calibrated. First, there are two district-specific vectors of parameters:  $\{A_i\}$ , the exogenous productivity of each district and  $\{H_i\}$ , the land endowment of each district. Then there are standard parameters present in other trade and spatial models. This is the case of  $\alpha$ , the share of tradable goods in total expenditure,  $\epsilon$ , the shape parameter of the Fréchet distribution from which idiosyncratic tastes are drawn and  $(\sigma - 1)$ , the trade elasticity. Finally, the model has three parameters related to the construction of infrastructure:  $\gamma$ , the elasticity of transport costs to infrastructure investments,  $Z$ , the budget of the government for infrastructure upgrades and  $\{c_i\}$  the district-specific marginal cost of construction.

**Standard parameters calibrated to exogenous values** I calibrate  $\{\epsilon, \alpha\}$  to existing values in the literature. I set the shape parameter of the Fréchet distribution to  $\epsilon = 3$  following the estimated value from domestic migration flows across U.S. counties by [Monte et al. \(2018\)](#).<sup>44</sup> I choose an expenditure share of tradables of  $\alpha=0.7$ , leaving an expenditure share of housing of  $(1 - \alpha) = 0.3$  following [Redding and Sturm \(2008\)](#) in their study about the population growth effects of the German division.

**Standard parameters calibrated to Germany 1938** The district-level land endowments,  $\{H_i\}$ , are equated to the surface of each district in squared kilometres as measured in the data.<sup>45</sup>

Given the land endowments, the district-level productivities,  $\{A_i\}$ , are calibrated to match the

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<sup>44</sup>A similar value of the shape parameter of the Fréchet function has been estimated using data on domestic migration in Indonesia ([Bryan and Morten, 2019](#)). Unfortunately, domestic bilateral migration flows are not available for Germany over this time period. [Ahlfeldt et al. \(2018\)](#) estimate a higher value of this parameter,  $\epsilon = 7$ , using commuting and mobility patterns within the city of Berlin, but we can expect worker to hold more heterogeneous preferences over locations across the country than within a single city.

<sup>45</sup>Since this land is not quality-adjusted or net land devoted to housing, I cannot use it to calibrate amenity parameters at the district level. I abstract from adding explicit amenities but still include land endowments to capture the differences in land extension across districts. German districts, *Kreise* are on average  $300 \text{ km}^2$  but some of them are urban districts, much smaller than this. The land surface of a district will create an additional dispersion force that increases the range of parameters for which the model will have a unique and stable equilibrium.

population distribution of Germany in the year 1938. I compute the productivity level of each district by inverting the spatial equilibrium and solving for the vector of district productivities that, in equilibrium, delivers the population distribution observed in the data.<sup>46</sup> I use population at the district-level for 1938 from the German Census collected in the Statistical Yearbooks of the Federal Republic of Germany.

**Parameter estimated using the full-structure of the model: Trade elasticity** Finally, I use data on shipments by road over 10 distance brackets in 1938 to calibrate the trade elasticity parameter  $(1 - \sigma)$ . For this estimation I use the full structure of the model with fixed infrastructure. First, I estimate the elasticity of trade shipments to distance using historical data of shipments and obtain an estimate of  $\beta = -2.8^{***}$ . This estimate is larger than the average magnitude estimated in the literature of around 1 but transiting through ground-transport means, such as roads, has been shown to yield substantially higher distance coefficients (Disdier and Head (2008)).

Under the standard assumptions of the gravity equation this elasticity is the product  $\beta = (1 - \sigma) \times \nu$ , where  $\nu = \partial \log(T_{i,j}) / \partial \log(\text{dist}_{i,j})$ . Given the lack of data on transportation costs, the consensus in the literature has been to choose  $\nu = 0.3$  (Monte et al. (2018) among others). This less than proportional change of transport costs to distance can be accounted for by the existence of fixed costs in shipping and by the choice of optimal transit routes, for example using highways for longer distances.<sup>47</sup>

To select a value of  $\sigma$  that delivers the estimated elasticity of  $\beta = -2.8^{***}$  we need to estimate the elasticity  $\nu$  in 1938 as implied by my model. To this end I set the elasticity of substitution to  $\sigma=5$ , following the consensus in the trade literature (for example (Broda et al., 2008)), and compute the implied trade flows across all district pairs conditional on the parameter values chosen above and the network in 1938. The elasticity of trade shipments to distance in the model with  $\sigma = 5$  is

<sup>46</sup>This calibration technique is explained in the survey by Redding and Rossi-Hansberg (2017)

<sup>47</sup>My model does not have an exact counterpart to  $\nu$  but this distance to transport cost elasticity will emerge from the assumption that transport costs are minimised (choice of shipping using the least-cost path).

$\beta^{model} = -1.84^{***}$ , which implies a value of  $\nu = \partial \log(T_{i,j}) / \partial \log(dist_{i,j}) = 0.46$ .<sup>48</sup> Given  $\nu = 0.46$ , I set  $\sigma = 7$  in order to achieve an elasticity of trade flows with respect to distance that matches the estimated elasticity in the data of 1938 ( $\beta^{model} = -2.8$ ). Table D.2 in the Appendix shows that the elasticity of trade shipments to distance in the model, when I use it to simulate trade flows and aggregate them by distance brackets as in the data, is  $\beta^{model} = -2.78^{***}$ , equal to the elasticity estimated in the data.

Together with this value of the trade elasticity,  $(1 - \sigma) = -6$ , the choice of parameters described above ensures that the condition for the existence of a unique and stable spatial equilibrium is fulfilled.

**Parameters related to Infrastructure-choice** The three parameters specific to my model are  $\{c_i\}$ , the district specific marginal construction cost,  $\gamma$ , the returns to infrastructure investments and  $Z$ , the government's budget to invest on infrastructure. Recall that the budget constraint of the government is:

$$\sum_{i=1 \dots N} c_i \phi_i \leq Z, \quad (25)$$

where  $\{\phi_i\}$  is the vector of infrastructure investment allocations. Because the initial underlying grid is taken from the existing highways and roads in place in 1930s Germany these links will already be, to some extent, equally easy to build on. This means that the set of links that are upgradable in the model are roads and federal roads already developed. The initial costs, such as the levelling the terrain, will have been paid already by previous developers. Indeed, most of the highways that are built over the years are built on or at the side of previously existing roads. Thus, I choose  $c_i = c, \forall i$  to simplify the computation problem. However, the ruggedness of the terrain or the existence of rivers could be introduced easily in the problem by allowing this cost to vary with terrain characteristics.

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<sup>48</sup>Since my calibration only features federal roads and local roads, the elasticity of transport costs to distance is higher than the estimation in papers using more modern data. This elasticity will go down as I allow for highways to be built.

The parameter  $\gamma$ , the returns on infrastructure investments, determines whether infrastructure investments have increasing or decreasing returns. Therefore, this parameter will shape the concentration of highway investments at the district level. The idea is that highway construction cannot be accumulated without limit in a given district. After a certain amount of kilometres, the transport costs will not go down further. I estimate  $\gamma$  to bring the degree of concentration of investments in the model as close as possible to the concentration in the 1934 Plan.<sup>49</sup> As a measure of concentration of investments I use the skewness of the distribution of highway kilometres in the 1934 highway plan. I use the Simulated Method of Moments (SMM) on a simulated 50-district economy where I discipline the productivity distribution using random draws from a distribution similar to the calibrated productivities in the previous section. This estimation yields parameter  $\gamma = 0.84$ , showing that highways indeed present marginal decreasing returns. Figure D.7 in the Appendix shows that the distribution of the model's predicted investment is almost identical to the distribution of highway kilometres in the 1934 Highway Plan. Further details are provided in section B of the Appendix.

Finally, I calibrate the budget of the government,  $Z$ , to the total investment in the highway network. The budget in the model does not have an exact data counterpart in terms of units, since the vector of investments  $\{\Phi\}$  is a measure of how much transports costs will be reduced, in ad-valorem terms. To calibrate the model's budget, I need a measure of the total transport costs reduction, as implied by the growth in trade flows within Germany. I use the growth in aggregate traffic flows by road within Germany between 1952 and 1974 to calibrate the level of highway investments by 1974. The evolution of domestic traffic flows by mode of transport is reported in table D.1 in the Appendix. I calibrate  $Z$  in the post-division period to match a 3 fold increase in traffic by road, which is the average change in road traffic (long and short distance), after subtracting the growth in traffic by rail that I use as a proxy for overall economic growth. Once I have calibrated the post-division budget, I scale it up by 30% to find the pre-division budget, given the difference in length between the original 1930 Plan and the highways built before and after division. Full details are provided in

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<sup>49</sup>This is the only parameter that uses information from the 1934 Highway Plan. To estimate  $\gamma$ , I use the distribution of investments across districts in relative terms (as shares) since I will calibrate the aggregate level of investments with the parameter of the budget,  $Z$ .

section B of the Appendix.

## **B MODEL VALIDATION TESTS: CROSS-SECTION AND DIVISION OF GERMANY**

Given the description of the calibration and estimation of the model, I perform some over-identification tests to build confidence on the quantification of the model. I run two sets of tests. First, I show that the model is able to capture the cross-sectional distribution of economic variables before the Division, in the 1930s. Second, I exploit the unexpected division of Germany to test the predictions of the model on the evolution of economic outcomes after the division shock. I use population, trade flows and, most importantly, highway allocation in the data to show that the calibration of the model performs well.

### ***B.1 Model validity before division***

The equilibrium population allocation in the model before division is fit perfectly through the calibration of the productivity parameters. In this subsection, I provide two tests of the model fit before division.

**Trade flows before division** To check the model fit, I solve for the spatial equilibrium given the network of 1938 and the calibrated parameters. I aggregate total predicted trade by district into a different classification, traffic-districts (*Verkehrsbezirken*), for which I observe road shipments in the historical data. The data provides a measure of the total tons of goods received by road in any traffic-district from the rest of Germany and of total tons shipped to the rest of Germany. This information is available for 18 traffic-districts (that contain all 412 districts in Germany). I compare the predicted trade in the model with the total imports and total exports of each traffic-district in the data.

The correlation between the model and the data is  $\text{corr}=0.59$  for total imports ( $\text{Rsqr}=0.35$ ) and

$\text{corr}=0.70$  for total exports ( $R_{\text{sq}}=0.50$ ), as can be seen in Figure D.8 in the Appendix. Thus, the calibration presented in the previous sub-section does a good job replicating trade flows across German districts before division. This is not surprising since urban models of this kind have been successfully used to explain economic variables such as population and trade.

**Highway Plan** I now check whether the model is able to capture the incentives to build transport infrastructure that we see in the data. I solve for the predicted highway investment before division. Remember that the solution of the model yields the share of the investment budget that should be allocated to each district to maximise aggregate Welfare. I compare the investment allocation in the model with the highway kilometres per district in the 1930 highway Plan, represented in Figure D.2 in the Appendix. If the model is well specified, capturing part of the incentives behind highway planning, the investment allocation should be able to explain highway allocation in the data. As mentioned before, the 1930 Highway Plan was very similar to the one adapted by Minister Todt for Hitler in 1934 but was proposed by a group of engineers lobbying to build a german-wide highway network. Therefore, I believe it is a good representation of the incentives to build a highway network in 1930s Germany.<sup>50</sup>

To compare both allocations, I convert the share of investment into highway kilometres by assuming that the number of kilometres built in the model is the same as the total kilometres in the Highway plan of 1930. Figure IV plots the optimal number of kilometres per district in the model solution (upper figure) and the number of kilometres per district allocated in the engineer's Plan (lower figure). The shading represents the number of kilometres of investment predicted by the model or allocated in the plan in each district.<sup>51</sup>

[FIGURE IV ]

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<sup>50</sup>In the 1920s German politicians discussed the construction of a modern highway system. They formed the HAFRABA association that lobbied for the construction of a restricted access motorway connecting Hamburg-Frankfurt-Basel and other connections between major cities, driven by economic incentives (Zeller and Dunlap, 2010). Comparing the model's solution to the 1934 Plan would not be appropriate since Hitler's incentives to build the highway network may not be well captured by the model's assumptions.

<sup>51</sup>I convert investment units in the model to kilometres as explained in section D.4 of Appendix B.

The model is able to predict the main patterns of investment. First, the concentrations of investments around the biggest population centre, Berlin. Second, the radial structure of the network such as the connections of the main German cities to Berlin. In addition, the model seems to capture the relative importance of the different highway links. Notice that the darkest shades, investments with highest marginal return, coincide with the first highways, built in the decades of 1930 and 1940, as shown in figure D.9 in the Appendix.

Finally, and as expected, the model under-predicts investments at the border because the baseline model abstracts from international trade. I introduce international trade in the solution to the optimal investments post-division to understand the relevance of trade as a driver of infrastructure construction.

It is also worth noting that comparing the district to district investment levels does not capture the network structure of highways but takes districts as independent observations. To capture the spatial nature of the data, I compare the changes in bilateral transport costs that each district would enjoy after the construction of different data-driven and model-generated networks. I use the model to calculate the matrix of ad-valorem transport cost under the 1938 network, without highways, under the model's predicted network and under the Highway Plan of 1930. To test the model's performance, I run the following regression,

$$\Delta \text{Transport costs}_{i,j}(1930Plan) = \beta \Delta \text{Transport costs}_{i,j}(Model) + v_{i,j} \quad (26)$$

where  $\Delta \text{Transport costs}_{i,j}(1930Plan) = TC_{ij}^{Plan} - TC_{ij}^{1938}$ , the difference in bilateral transport costs given the road network of 1938 and the complete construction of the Highway Plan. The right hand side variable is  $\Delta \text{Transport costs}_{i,j}(Model) = TC_{ij}^{Model} - TC_{ij}^{1938}$ , the difference in bilateral transport costs given the road network of 1938 and the model-predicted highway allocation.

The results of this regression are displayed in the first column of Table II. The coefficient of the predicted transport cost variable is positive and significant. Most importantly, the model explains most of the change in transport costs that would have taken place if the Highway Plan had been built

( $R^2 = 0.70$ ). This means that the district-pairs that would have become better connected according to the construction of the Plan are the same district-pairs that would have become better connected under the model-generated network.

[ TABLE II ]

These results suggest that a model with endogenous infrastructure investments performs well in predicting the cross-section of highway investments as designed in the 1930's Plan outline.

## ***B.2 Model validity after division***

I now provide a more demanding test of the ability of the calibrated model with endogenous infrastructure to explain economic outcomes. I exploit the unexpected appearance of a border between East and West Germany after the Second World War, as a result of the increasing tensions the United States and the Soviet Union. While the division was supposed to be temporary, it became permanent once the conflict between these two countries escalated. The division of Germany can be used to test whether the structural model can capture the reaction of the economy to this division shock, that unexpectedly changed the trade partners and centrality of all West German districts. Relevant previous work in [Redding and Sturm \(2008\)](#) has shown that an economic geography model like the one I use in this paper can successfully capture the population response to the division shock of the largest West German cities. My results confirm these findings and extend the explanatory power of the model to infrastructure investments.

This exercise will serve as an over-identification test, since the calibration is based on pre-division data only. To perform this test, I simulate the division of Germany by dropping all East-German districts from the set of possible trade partners and location destinations. In addition, the new government's problem is now to maximise the aggregate welfare of West German districts. Finally, I impose some constraints on the government to reflect the fact that around 2000 kilometres of highways had been built between 1934 and 1950 (Figure I). To capture this physical constraint, I



add the following lower bound constraint:

$$\phi_j^{Postdivision} \geq \phi_j^{Predivision}. \quad (27)$$

This constraint will allow us to compare the constrained solution in the model with the constrained solution in the data. Finally, I assume that all other structural parameters remain unchanged.<sup>52</sup> In this assumption, I follow [Redding and Sturm \(2008\)](#) that interpret the division of Germany as mainly a trade and labour shock. They provide strong evidence showing that other factors such trends in specialisation, or the fear of further armed conflict were important but to a much lesser extent compared to the trade shock. However, in my analysis I consider the integration of Western European countries after 1960 in the framework of the European Economic Community. I describe this extension below.

**Population mobility after division** I perform two standard quantitative tests to show that the model can explain population and trade changes in the post-division period.

First, I test whether the district-level population change between 1950 and 1974 in response to the division shock confirms the model's assumptions. I focus on movements between 1950 and 1980, to avoid population changes around the time of the war, and I use the theoretical model to predict population changes as a function of observables. Taking logs and first differencing the population mobility condition, equation 14, we get the following expression for the change in population in region  $i$  between  $t$  and  $t-1$ :

$$\Delta \ln L_i = \frac{\epsilon \alpha}{(\sigma - 1)} \Delta \ln MA_i + \epsilon \Delta \ln v_i + \epsilon(1 - \alpha) \Delta \ln r_i - \Delta \ln L \quad (28)$$

where  $MA_i$  stands for the canonical Market Access measure,  $MA_i = \sum_j T_{ij,t}^{1-\sigma} E_{i,1938} / MA_{j,t}$  and  $E_{i,1938}$  stands for expenditure in district  $i$ . Notice that I am just re-writing the Price Index in region  $i$  in terms of Market Access ([Donaldson and Hornbeck, 2016](#)). I follow [Redding and Sturm \(2008\)](#) in

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<sup>52</sup>Table D.3 in the Appendix summarises the calibrated and estimated values for all parameters.

the view that the division of Germany can be summarised as a shock to market access and exploit the division shock to test equation 28 in the data.

I build  $\Delta MA_i$  as the difference between  $\ln MA_{i,1950}$  and  $\ln MA_{i,1938}$ .<sup>53</sup> I use population as a proxy for expenditure and fix population in the Market Access formula to the year 1938 to avoid endogeneity concerns. Thus, the only difference between  $MA_{i,1950}$  and  $\ln MA_{i,1938}$  is the change in transport costs coming from the division shock. To capture long-term changes, I compute a second measure of  $\Delta \ln MA_i^2$  that includes the new highway construction between 1950 and 1975. I define  $\Delta \ln MA_i^2 = \ln MA_{i,1974} - \ln MA_{i,1938}$ , capturing both the division shock and the new road construction between 1950 and 1974.

There are two empirical challenges to estimate equation the effect of market access changes on population, implied by equation 28. First,  $v_i$  and  $r_i$ , disposable income and rent are unobserved and will be contained in the error term. I control for the distance to the internal German border, to take care of the effects that the closeness to the border could have had on rents and wages (on top of the market access shock). In addition, I add state fixed effects to control for state-level differences in economic development, specialisation or state legislation.

The second challenge is that the change in Market Access could be affecting more strongly specific regions, creating a selection bias. This is specially worrying when we use the second measure of Market Access change,  $\Delta \ln MA_{1974,1938}$  because part of the variation comes from highway construction. As we know, governments may choose highway allocation based on economic fundamentals such as past or predicted internal migration or local growth. To deal with this endogeneity problem, I instrument  $\Delta \ln MA_{1974,1938}$  with  $\Delta \ln MA_{Plan,1938}$  where I measure the change in transport costs using the (counterfactual) 1934 Plan. Since the 1934 Plan pre-dates the division it

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<sup>53</sup>I compute the market access measure  $MA_{i,t}$  as the solution to the system:

$$MA_{i,t} = \sum_j \frac{T_{ij,t}^{1-\sigma} E_{i,1938}}{MA_{j,t}} \quad (29)$$

where  $E_{i,1938}$ , expenditure in the model, is replaced by  $L_{i,1938}$  population in district i in year 1938 and kept constant for all Market Access calculations to avoid endogeneity concerns.

could not be targeting economic outcomes in the Post-division period.<sup>54</sup> Given the above concerns, I run the following regression at the district level:

$$\Delta \ln \text{Population}_i^{80,50} = \beta_1 \Delta \ln \text{MA}_i + \beta_2 \text{Dist2border} + \delta_s + \nu_i \quad (30)$$

The results from the first stage regression are reported in table D.4 in the Appendix, showing that the 1934 Plan is a good instrument for the 1974 highway network (F-stat=47.7). Table D.5 in the Appendix reports the second stage results.

As we can see, the effect of a change in Market Access on population is positive and significant, confirming that the economic geography of West Germany can be captured by the forces in the quantitative model. I find that a 1% reduction in market access generates a 0.23% (s.e. =0.073) drop in population (column 3, IV estimation). This effect is very close to the magnitude suggested by the model according to equation 28, equal to  $\frac{\epsilon\alpha}{(\sigma-1)} = 0.35$ . The IV result (column 3) is larger than the OLS result (column 2), showing that highways were partly allocated to regions lagging behind.

**Trade costs after division** The second test I conduct is to compare the predicted change in domestic trade flows with the changes in the domestic traffic data. In this test I assess whether the calibration of transport costs and infrastructure improvements in the model generate a response comparable to the data. I collect traffic flows between west German states in 1960 and in 1989.<sup>55</sup> I use the model to predict the change in trade flows between 1960 and 1980 and compare the response of trade to trade costs in the model and in the data.<sup>56</sup>

As a measure of change in transport costs, I compute the change in ad valorem transport costs for every district-pair for the highway network in 1950 and the highway network in 1980. This

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<sup>54</sup>Historical infrastructure plans have been used as an instrumental variable strategy in previous research, like (Michaels, 2008) among others.

<sup>55</sup>The change in trade flows is computed as the growth rate of trade flows across German states (log-change). The data is in tons while the simulated data from the model is in nominal value of flows.

<sup>56</sup>The trade flows for the years 1960 and 1989 are generated by solving the spatial equilibrium of the model setting the total population to the 1960 (1989) and the highway network to the observed 1960 (1989) highways.

variable,  $\Delta TC$ , is always negative going from 0 to -2 (zero change up to 200% reduction). I measure transport cost improvements one decade earlier than the trade flows to allow for firms and consumers to adjust to the new infrastructure. Then, the changes in transport costs are aggregated to the state level by taking simple means to compute the state-to-state change in ad-valorem transport costs.<sup>57</sup> I run the following regression using historical data as well as model-generated data:

$$\Delta \ln Trade_{s,s'}^{1960,1989} = \mu_1 \Delta TC_{s,s'}^{1950,1980} + v_{s,s'}, \quad (31)$$

where  $s, s'$  are two states in West Germany and  $TC$  is the ad-valorem average transport cost computed along the least-cost path given the highway network.

[TABLE III]

Table III reports the relation between log-changes in trade flows and changes in transport costs. It confirms that the model is able to capture remarkably well the response of trade flows to reductions in transport costs when we account for the change in highways (column (1) vs column (2)). According to these results, a pair of states that benefited from a reduction in the ad-valorem transport cost similar to the mean ( $\Delta TC_{s,s'}^{1950,1980} = -1$ ), saw an increase in trade flows of 19.5% in the data and of 14.5% in the model.

These tests confirm that the static model built in section III performs strikingly well in predicting the population response to the division as well as the long-term changes in trade flows after division.

**New highway construction after division** Finally, I check whether the model is able to predict the highway reshaping that took place after the division, documented in section II. I use the model to predict highway construction after the division, given the highways that had been built until 1949.

An empirical challenge that we face when analysing highway construction in the cross-section is

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<sup>57</sup>District to district historical trade flows are not available in a digital form and collection would be possible but very costly, so I use an aggregate version of the data instead.

that highway construction may be driven by district-specific factors affecting other fundamentals.<sup>58</sup> This type of factors would induce a bias in the estimation of the predictive power of the model. To avoid these challenges I focus on the change in highway construction that controls for the presence of time-invariant characteristics. This is the first paper to test the predictive ability of a model with endogenous infrastructure choice by controlling for time-invariant factors.

Figure V plots the spatial distribution of highway investments predicted by the model and in the data. The above panel shows the difference between the predicted investments in the model and the highways built by 1949. The lower panel shows the district-level change in highway construction in the data. The shades represent the investment allocation predicted by the model, with darker shades representing higher investments.

The efficient (constrained) network is the pattern highway investments that we would observe if the government's choice was driven by the mechanisms captured in the model. It is worth noting that both allocations feature two North-South connexion lines, showing the re-orientation of the network. The model's solution concentrates investments heavily on this North-South orientation. On the contrary, actual highway construction was also allocated to districts near the new border, in a Northwest to Southeast direction.

[FIGURE V ]

To test the predictive power of the model, I focus on the optimal change in bilateral transport costs predicted by the model and compare it to the transport cost change implied by the data. I run a regression that correlates the change in ad-valorem transport cost between 1950 and 1974 with the model-implied change in ad-valorem transport cost under the assumption that the construction after

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<sup>58</sup>For example, districts in the mountains have less population and trade less goods because of their remoteness and, at the same time, receive less highway construction because of the low demand for transport and the high construction cost. Thus, the elevation of the terrain creates a positive correlation between economic fundamentals and highway construction. I do not take into account elevation in my calibration of construction costs because I only allow for highway upgrading on top of former local or regional roads, so the initial cost of crossing a mountain will have already been paid by the previous road planner. In the same sense, specially challenging terrains will not have been chosen to build local and regional roads.

1950 follows the model solution:

$$\Delta \text{Transport costs}_{i,j}(1974, 1950) = \beta_1 \Delta \text{Transport costs}_{i,j}(\text{Model}) + v_{i,j}, \quad (32)$$

where  $\Delta \text{Transport costs}_{i,j}(1974, 1950)$  is the change in bilateral transport costs between years 1950 and 1974, between districts  $i$  and  $j$ , and  $\Delta \text{Transport costs}_{i,j}(\text{Model})$  is the change in bilateral transport costs between 1950 and the model's efficient network.

Table II, displays the results in columns 2 and 3. The model does a very good job at predicting the change in transport costs during this period, explaining 97% of the change in transport costs. As a reference point, the model outperforms the 1934 prewar plan, that explains 92% of the variation. These estimates suggests that the model is able to anticipate which districts became relatively better connected after the division.

## C DISCUSSION OF MODEL PREDICTIONS

**International trade and highway choice** The main challenge to identification the explanatory are changes in other factors, in addition to geography, happening right after the division of Germany and affecting the returns to highway construction unevenly across the West German geography. Factors affecting all West German regions simultaneously such as the destruction and re-construction of cities after the Second World War or the decline in the importance of the railway as the main mode of transport for freight should not bias the estimates presented in the previous subsection.<sup>59</sup>

As long as the effect is mostly constant across all regions, these changes create a level effect that would be differenced out in the proposed estimation strategy. However, changes affecting West German regions in an uneven way could bias the estimation of the predictive power of the model. One of such factors is the process of European integration during which tariffs to international trade

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<sup>59</sup>Redding and Sturm (2008) show that war-time destruction and industrial specialisation patterns were uncorrelated with proximity to the new inner German border.

were eliminated between Belgium, Italy, Luxembourg, Netherlands and West Germany. This process started with creation of the European Economic Community in 1957 with the Treaty of Rome. Notice that this process of international integration would increase the incentive to build highways towards the West in the same way in which the division of Germany would reduce incentives to build highways towards the East.

To account for this, I extend the model to allow for international trade with other West European countries and re-compute the optimal highway investments. In a nutshell, I recalibrate the productivity parameters to capture that the regions at western border became more “attractive” once it was possible to trade at lower tariffs with Western Europe. Details about the introduction of international trade in the model can be found in section B of the Appendix.

Figure D.10 in the Appendix plots the optimal change in highway construction as predicted by the model with international trade (above panel) and the observed change in highway construction between 1950 and 1974 in the data (lower panel). The model with international trade predicts a shift of infrastructure towards the western border of Germany and smaller investments near the inner German border.

The results from the model extended with international trade are reported in Table D.6 in the Appendix. The optimal highway investment in the model still has good predictive power for the actual change in transport costs, and has essentially the same predictive power as the model without international trade (the R-squared of column 3 is 96.8% in the extended model compared to 97% in the baseline model, column 1). Since the model with international trade predicts too much investment near the western border compared to the data ( see figure D.10 in the Appendix), it seems unlikely that the European integration process was the main motive behind highway reshaping.<sup>60</sup>

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<sup>60</sup>One explanation for why the model with international trade over-predicts investments in the West could be that in the first years of the European integration process international trade was still moderate in magnitude as a share of domestic activity. Thus, infrastructure investments did not shift as fast toward the West as the extended model would predict. In particular, in the year 1982, around 85% of all tonnes-kilometres shipped in West Germany by road were domestic shipments while only 15% were cross-border (international) shipments.

**Further objectives driving highway choice** Additional factors that we could consider are changes in the industrial composition of West Germany or the shift of the capital from Berlin to Bonn. Extending the model to account for industrial policy or for the benefits of a change in the capital city goes beyond the scope of this paper. However, the interplay between infrastructure policy, industrial policy and the institutional setting is a promising avenue for future research. For example, [Bai and Jia \(2018\)](#) show how the loss and gain of regional capital status in China was accompanied by upgrades in the transport network. This change in status results in a gain or loss of centrality of a given city in the transport network, creating a link between the political and the economic status of the city.

Finally, part of the 1974 followed the 1934 prewar plan. As documented in section [II](#), while the first two thousand kilometres of highway built before the division followed the prewar plan, only half of the highways built after division were constructed following the plan. Further work could be directed to understanding why the West German government completed part of the 1934 design, rather than fully optimising the network.

The empirical tests reported in this section have shown that the quantitative model is able to capture the economic geography of Germany as well as the incentives driving highway construction, both before and after the division. Given the confidence that we have built on the model, I use it to quantify the economic impact of highway investments in two counterfactual exercises. First, I examine the gains from the partial reaction of the government to the shock, comparing the welfare level for the observed highway network with the counterfactual of building the 1934 highway Plan. Second, I quantify the cost of rigidities in the choice of infrastructure, coming from the initial two-thousand highway kilometres built before the division.



## **V    QUANTIFICATION: GAINS FROM RESHAPING INFRASTRUCTURE**

In this section, I quantify the aggregate gains from flexible infrastructure choice. I use the structural model to perform two policy-relevant counterfactuals.

First, I ask whether governments can affect aggregate welfare by placing infrastructure in a sensible way, taking into account the economic geography of a country. To understand this, I take a data-driven approach: I quantify the gains in welfare accomplished by the reshaping of the highway network that took place after the division of Germany, as documented in [section II](#).

Second, I study whether past infrastructure construction can shape future infrastructure investments through path-dependence. Infrastructure projects are long-lived and, therefore, can become obsolete after unexpected changes in the economic geography of a country. The construction of the first part of the prewar highway Plan and the subsequent division of Germany is an extreme, but clear, example. To explore the cost of infrastructure rigidity, I solve for the efficient unconstrained highway network, assuming no highway development had taken place before division, and quantify the cost of path-dependence by comparing it to constrained efficient network.

### **A    GAINS FROM PARTIAL-RESHAPING AFTER DIVISION**

First, I aim to understand how much West Germany benefited from the ability to reshape the highway network after the division. To do so, I compare the observed highway network in the year 1974 with the 1934 highway Plan. Comparing the actual highway network in 1974 with the 1934 Plan has two advantages: First, the counterfactual comes directly from the data, and uses the revealed choice of two different governments: the West German government and the 1930s German government. Second, both networks are of the same length, in terms of highway kilometres. Thus, differences in the aggregate benefits of these two networks come purely from the reallocation of construction across districts.

Figure VI shows the spatial distribution of highway kilometres in the two networks in the top two panels: the 1934 Highway Plan in panel A and the highway network in 1974 in panel B.<sup>61</sup> As the figure shows, the network in 1974 was less dense near the eastern and the southern border, and denser towards the West.

[FIGURE VI]

I use the model as a measuring tool to compute welfare gains from the construction of the 1934 highway Plan as well as from the 1974 highway network.<sup>62</sup> I think of the 1934 highway Plan as a counterfactual of the highway network that would have been built if the economic fundamentals in Germany had remained as they were in the 1930s. The 1974 highway network represents the response of the West German government to the division shock. It is worth noticing that the difference between the highway Plan and the 1974 network is about one third of the total highway development.

For the comparisons, I write welfare and income relative to the welfare and income in the equilibrium with zero highway investments. I compute the gains from these networks in two cases, the baseline model with no international trade and the extended model that allows for trade with Western European countries. The results are reported in figure VII.

The government's reshaping of the network post-division increased welfare by 16.06% relative to the no-highways equilibrium, while the 194 Plan would have increased welfare by 14.82%. Therefore, the 1974 network increased welfare by 1.24% relative to the 1934 Highway Plan. The gains in terms of real income were of 0.69% compared to the construction of the 1934 Highway Plan. It is important to remember that these gains come purely from the reallocation of the highway network keeping the budget fixed.

The gains from the observed reshaping of infrastructure are even larger if we consider the

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<sup>61</sup>This map is different from the one in the previous section because it represents the total number of kilometres built by 1974, not the new investments.

<sup>62</sup>Details about the construction of the model counterpart of the 1934 and 1974 network can be found in section B in the Appendix.

potential trade flows with European neighbours, with the gains increasing to 2.13% in terms of welfare and 2.07% in terms of real income. This means that, once we take into account the creation of the European Economic Community, the inefficiency of the prewar Plan is even larger. The inefficiency comes from the excessive investments that the Plan allocated in the East relative to North-South links and investments near the western border. These results show that the ability to reshape the transport network in response to large economic changes is crucial for aggregate outcomes.

[FIGURE VII]

## **B COST OF RIGIDITY DUE TO PATH-DEPENDENCE**

Finally, this setting allows me to quantify the cost of rigidities in the construction of infrastructure networks. Rigidity will be costly if the placement of past infrastructure investments determines the placement of future investments. In other words, if we observe path-dependence from past highway investments. The construction of the German highway network started in the 1930s when the division could not be anticipated. As documented in the paper, highways in the 1930s were built from the West to the East, ending in Berlin. The efficiency of these initial links was seriously affected by the appearance of the inner German border. Thus, this is a unique setting to evaluate the cost of an inefficient not being able to optimise the transport network due to initial conditions.

To understand whether these initial investments created path-dependence in the network, I use the calibrated model. I solve for the unconstrained infrastructure allocation in West Germany by assuming that no highway had been built before division. This solution represents the efficient allocation of highways if the West German government had started highway construction after the division. I compare it to the solution found in section IV, where I used the model to predict the efficient investment subject to the prewar highway construction.

Figure VI shows the spatial distribution of investments in the two counterfactual networks in the

two bottom panels: the constrained network in panel C and the unconstrained network in panel D. The investment solution found in the unconstrained case is different from the solution found in the constrained case. As the figure indicates, the unconstrained network concentrates investments along the north-south direction and is less dense near the border with East Germany and Austria. This finding confirms that the initial highways built between 1934 and 1949 constrained the choice of the West German government and affected the placement of new investments.

To quantify the cost of these initial investments, I compare the aggregate welfare level of the economy under the efficient unconstrained network with the welfare level under the constrained network, that includes the highways built pre-division. Figure VIII reports the quantification results.

As in the previous quantification exercise, results are reported as a percentage of the welfare and real income levels in the no-highway equilibrium. I include the welfare and real income gains under the 1974 highway network as a reference. Taking the difference between the unconstrained and the constrained outcomes allows us to focus on the relative performance of the unconstrained versus the constrained network. The unconstrained network delivers 1.86% higher welfare and 1.82% higher real income than the constrained network. Notice that these numbers represent a large part of the total gains expected from the 1974 network. This estimated cost of path-dependence is very high, accounting to 11.5% of the total welfare gains from the 1974 highway network and 12% of the real income gains from the 1974 highway network. This is, to the best of my knowledge, the first quantification of the aggregate cost of path-dependence in the literature.

It is worth mentioning that the model-generated highway allocations deliver higher aggregate outcomes than the data-driven networks, as expected. The large gains predicted by these two counterfactual networks should be taken with a grain of salt. It is clear that the model abstracts from other factors that could affect aggregate welfare in the data. However, given that these additional factors not accounted for in the model are ignored in both alternative scenarios, the constrained and the unconstrained, I expect a similar bias in both of them. Thus, even if the total magnitude of the aggregate gains under these counterfactual networks may be exaggerated, we can learn something

about the differences between the two.

[FIGURE VIII]

## C DISCUSSION OF RESULTS

Finally, let us put in perspective the different welfare and real income gains associated with the different counterfactual networks.

The quantifications so far were considering the aggregate gains of different highway network allocations of the same length. What are the aggregate economic gains of infrastructure construction? Taking as baseline the 1974 highway network, I find that eliminating all highways would cause Welfare to fall by 16.06% and real GDP by 8.26%. As we mentioned before, if we change the 1974 Highway network by the 1934 Highway Plan, Welfare would fall by 1.24% and real GDP by 0.69%, thus by almost 10% of the total gains from building the 1974 highway network. This shows that the government's response to the division increased the gains from highway construction by a large magnitude.

These gains are in line with the findings by [Morten and Oliveira \(2018\)](#), that find welfare gains of 13.3% after the construction of the Brazilian highway network, but large relative to other estimates in the literature. For example [Asturias et al. \(2019\)](#) and [Alder \(2019\)](#) find gains of 2.7% and 2.53% of real income respectively from the construction of the Indian Golden Quadrilateral highway network. [Fajgelbaum and Schaal \(2020\)](#) find welfare gains of between 0.9% and 1.5% from re-optimising the totality of nowadays German highway network.

There are three main differences between my paper and these other studies. First, I examine the gains from reacting to a change in economic fundamentals. My findings suggest that the economic impact of infrastructure is larger when responding to a large geographic shock than in the presence of stable economic fundamentals. Second, my results are estimated from a very large expansion of the network. I evaluate the construction of five thousand kilometres in a country of three hundred and

fifty thousand square kilometres. [Asturias et al. \(2019\)](#) and [Alder \(2019\)](#) examine the construction of six thousand kilometres of highways in India, almost the same length, in a country ten times larger than Germany (3.1 million square kilometres). Finally, my findings come from evaluating the initial part of the highway network. It is likely that the returns to highway investments decrease as infrastructure is accumulated.

## VI CONCLUSION

The placement of transport infrastructure shapes the economic gains from infrastructure investments and the distribution of economic activity across space. However, transport policy involves long-term investments that persist over decades. Understanding how policy-makers can adapt infrastructure to changes in the economic environment is crucial to make good investment decisions.

In this paper, I take a structural approach to this question by building a quantitative spatial trade framework with endogenous infrastructure investments. In the model, the government decides how to allocate investments across regions to maximise aggregate welfare. This framework allows me to characterise the efficient infrastructure allocation and calibrate the model taking into account the endogeneity of infrastructure.

I use the calibrated model to quantify the aggregate gains from flexible infrastructure choice in the context of the division of Germany. The division of Germany allows me to study how the highway network was developed after the country was unexpectedly divided into East Germany and West Germany.

Using newly digitised data, I document that the West German government reacted to the division shock. In particular, half of the highway kilometres built after the division, between 1950 and 1974, deviated from the original prewar highway Plan. I find that the reallocation of these investments (one third of the network) led to increases of 1.24% of welfare and 0.69% of real income annually, keeping the budget fixed. In the extended model with international trade, the gains are even larger:

the 1974 highway network increased welfare by 2.13% and real income by 2.07% relative to the counterfactual construction of the prewar Plan.

Finally, I use the quantitative model to measure the cost of rigidity when developing the transport infrastructure. The highways built before the division had to be taken as given by the West German government after the division and created path-dependence. I find that the efficient unconstrained network could have increased welfare by 1.86% and real income by 1.82% relative to the efficient constrained network, that takes the prewar highways as given.

These gains are large relative to current estimates in the literature, probably because I evaluate the initial stages of highway development in a period of deep geographic and economic changes. This setting makes my results particularly relevant for countries going through deep structural reforms and large policy changes. Making use of a quantitative framework like the one developed in this paper can help governments quantify the expected gains across alternative infrastructure investments.

There are several related questions that need to be addressed in relation with infrastructure choice more generally. First, what other factors shape the investment decisions of governments? The importance of other factors, such as political incentives, can be estimated using a framework of endogenous infrastructure that considers a richer objective function for the government. Second, how do we choose the optimal amount of transport infrastructure, and how does it depend on additional mechanisms such as intermediate input usage or international trade? Finally, what is the best way to build in flexibility in settings when future outcomes can be difficult to predict, such as fast-urbanising emerging countries or deeply integrated areas undergoing political challenges? Expanding this framework in the mentioned directions is left for future research.

DEPARTMENT OF ECONOMICS AND CAGE, UNIVERSITY OF WARWICK

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## VII TABLES

TABLE I: Highway development - Planned kilometres as share of total kilometres built

Network	Included in the 1934 Highway Plan		Total
	Yes	No	
Highway km 1950 (2128 km)	95	5	100
Highway km 1950 to 1974 (3015 km)	47.2	52.8	100

**Notes:** Kilometres identified as included in the 1934 Plan are the kilometres that were planned and built, summed across all districts. Column 1 represents this value as a share of total built kilometres. Column 2 represents the remaining share of kilometres that were not planned but were built, in deviation from the Plan. The first row presents the decomposition of the 2128 kilometres built between 1934 and 1950 while the second row refers to the 3015 kilometres completed between 1950 and 1970.

TABLE II: Model Validity test- Infrastructure investments

Dep Variable	PRE DIVISION	POST DIVISION	
	$\Delta T_{i,j}(1930 \text{ Plan})$	$\Delta T_{i,j}(1974 - 1949)$	$\Delta T_{i,j}(1974 - 1949)$
	(1)	(2)	(3)
$\Delta \text{Transport Costs (Model pre-division)}$	0.5332*** (0.0025)		
$\Delta \text{Transport Costs (Model post-division)}$		0.7366*** (0.0006)	
$\Delta \text{Transport Costs (1934 Plan)}$			0.9760*** (0.0011)
Constant	-0.1148*** (0.0027)	-0.0389*** (0.0009)	-0.0756*** (0.0013)
Observations	77028	48206	48206
$R^2$	0.706	0.970	0.922
Mean dep. var	-0.78	-1	
SD dep. var	0.42	0.57	

**Notes:** Standard errors, are in parentheses.\* significant at 10%, \*\* significant at 5%, \*\*\* significant at 1%.  $\Delta T_{i,j}(1930 \text{ Plan})$  is the change in ad-valorem bilateral transport costs between all district-pairs delivered by the counterfactual construction of the 1930 Highway Plan.  $\Delta T_{i,j}(1974 - 1949) = T_{i,j}(1974) - T_{i,j}(1949)$  is the change in ad-valorem bilateral transport costs delivered by the upgrading of the highway network between 1949 and 1974.  $\Delta \text{Transport costs}_{i,j}(\text{Model pre-division})$  is the change in ad-valorem transport costs delivered by the model's predicted highways before division while  $\Delta \text{Transport costs}_{i,j}(\text{Model post-division})$  is the change in transport costs delivered by the model's predicted highways in the post-division period.  $\Delta \text{Transport costs}_{i,j}(1934 \text{ Plan})$  is the change in ad-valorem transport costs delivered by the counterfactual completion of the 1934 Plan. All transport costs are measured in the model, by assuming different infrastructure networks and computing the bilateral transport cost matrix.

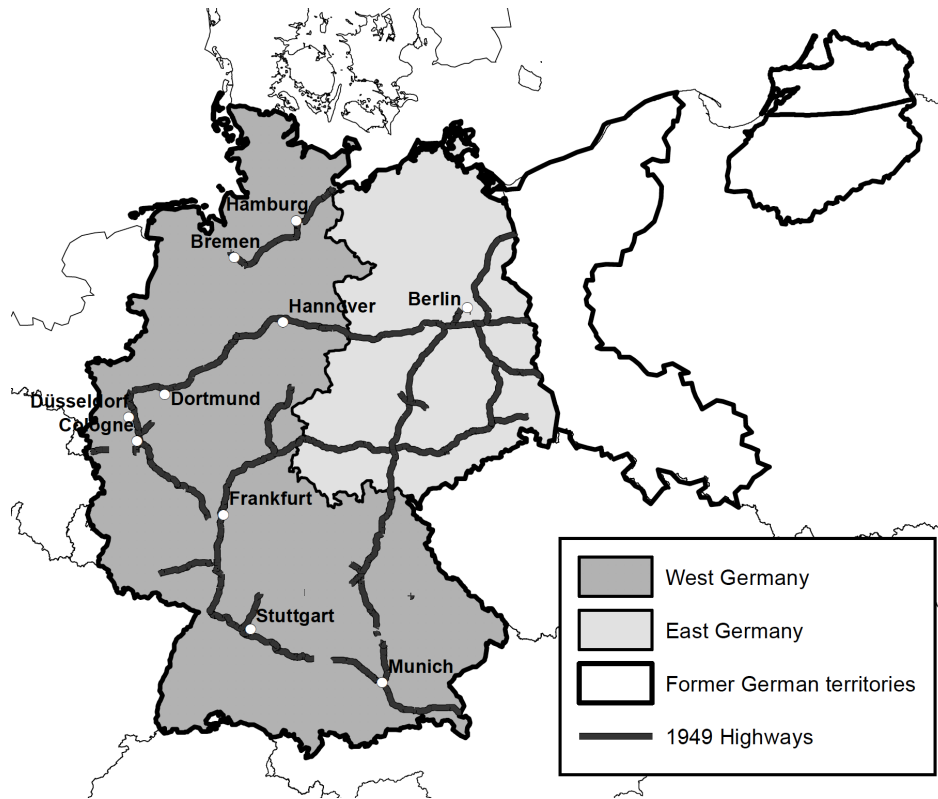
TABLE III: Model Validity Test: Change in trade flows 1960 to 1989

Dep. Var: $\Delta \log(Trade_{i,j})$	Data	Simulation
	(1)	(2)
Change in Transport costs (1980-1950)	-0.195*** (0.0542)	-0.145** (0.0613)
Constant	0.714*** (0.0597)	0.295*** (0.0711)
Obs.	90	90
R-Squared	0.117	0.0435
Mean Change	-0.995	
St. Dev Change	0.51	

**Notes:** Standard errors, are in parentheses.\* significant at 10%, \*\* significant at 5%, \*\*\* significant at 1%. Outcome variable  $\Delta \log(Trade_{i,j})$  in the Data (column 1) is the log-change in tons shipped across each pair of West German states. The outcome variable in the Model (column 2) is the log-change in nominal value of state-to-state trade predicted by the model. The Change in Transport costs (1980-1950) is computed as the average reduction in ad-valorem transport costs across each state-pair between 1980 and 1960. It is measured as the difference in ad-valorem transport costs that would materialise by upgrading the highway network in 1960 to the highway network as it was in 1980. This variable is always negative going from 0 to -2. The changes in transport costs are aggregated by taking simple means to compute the state-to-state change in transport costs.

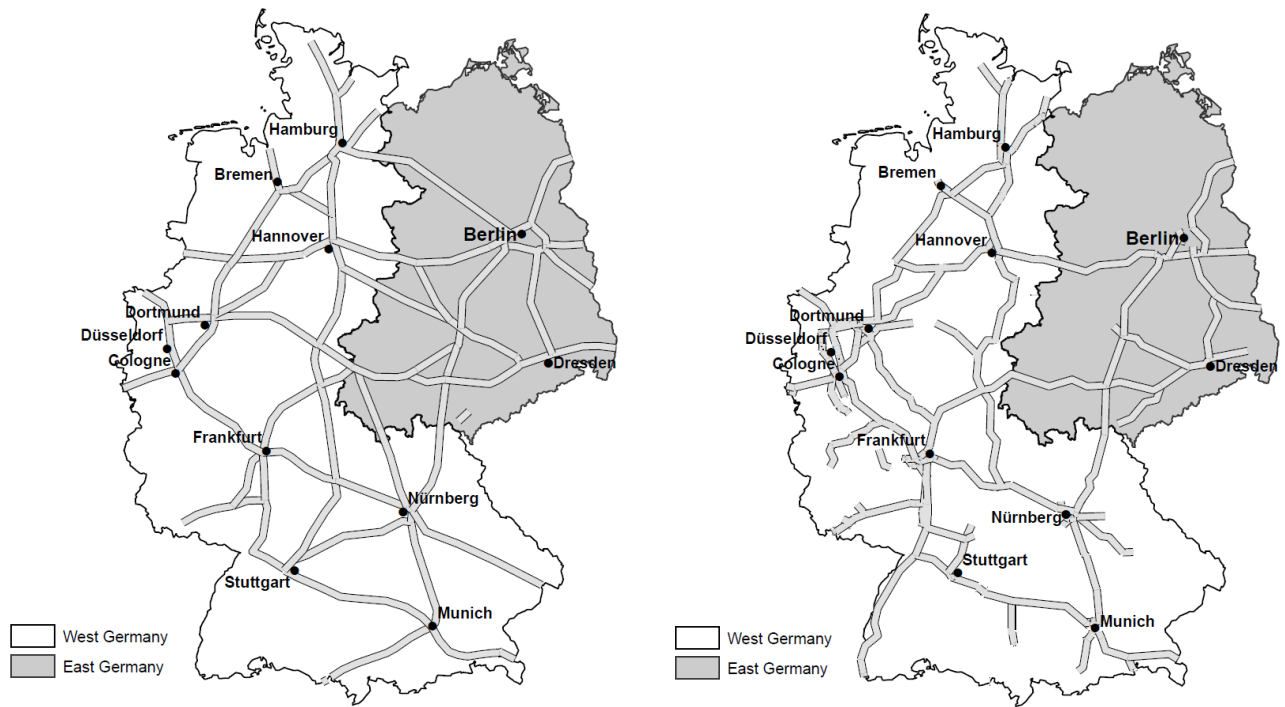
## VIII FIGURES

FIGURE I: The division of Germany and the highway network in 1949



**Notes:** The figure displays West Germany (dark grey) and the former German territories of East Germany (light grey), Prussia and East Prussia (light grey). The highways built by the year 1949 are depicted as black lines. Source: Created by the author from newly digitised historical data.

FIGURE II: The 1934 highway Plan and the Post-Division highway network



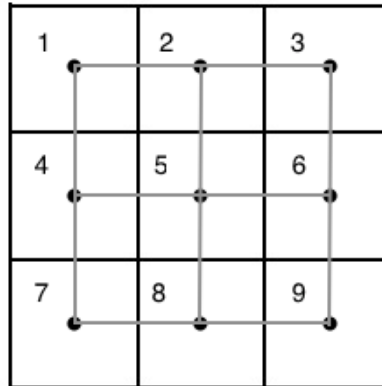
**A: 1934 Highway Plan**

**B: 1974 Highway network**

**Notes:** Panel A presents the outline of the 1934 Highway Plan over Germany's border. Panel B presents the German highway network built by the year 1974.

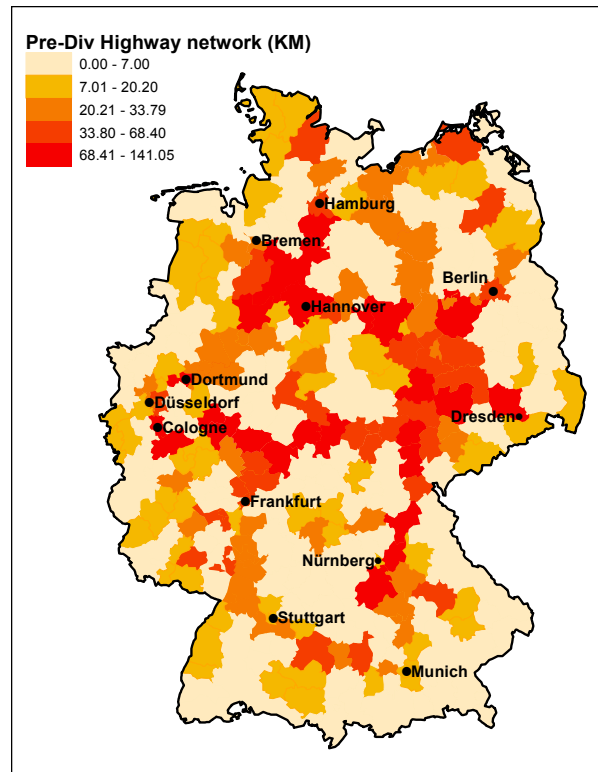


FIGURE III: Example of simple geography

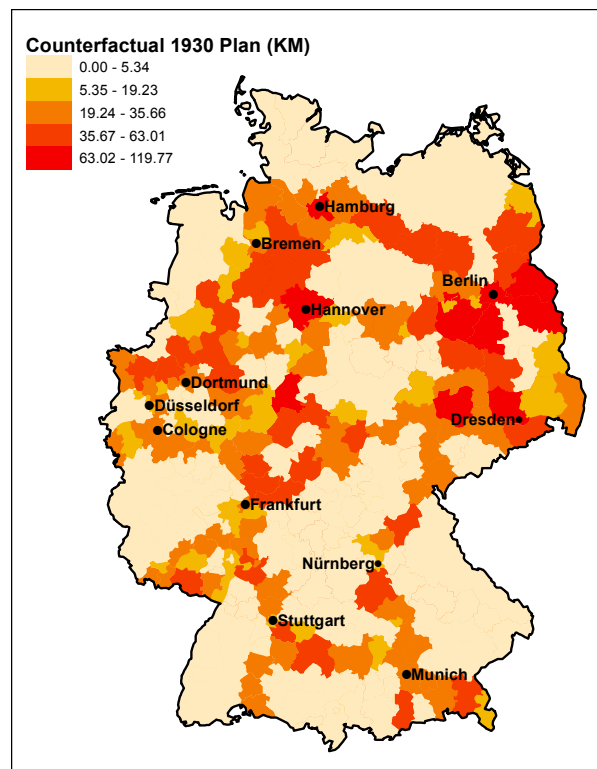


**Notes:** Geography with 9 regions; dots are the population centres. In grey the initial transport network, with the same initial quality.

FIGURE IV: Simulated Infrastructure investments before the division shock



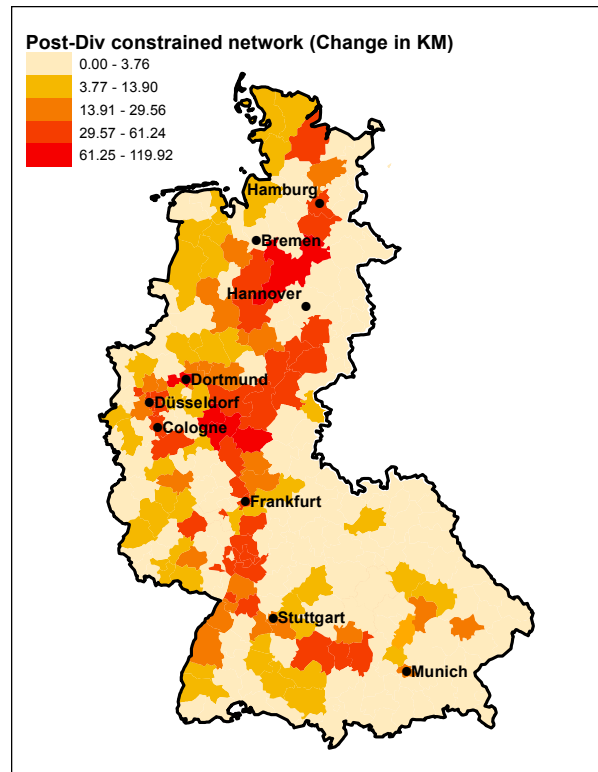
A) Model



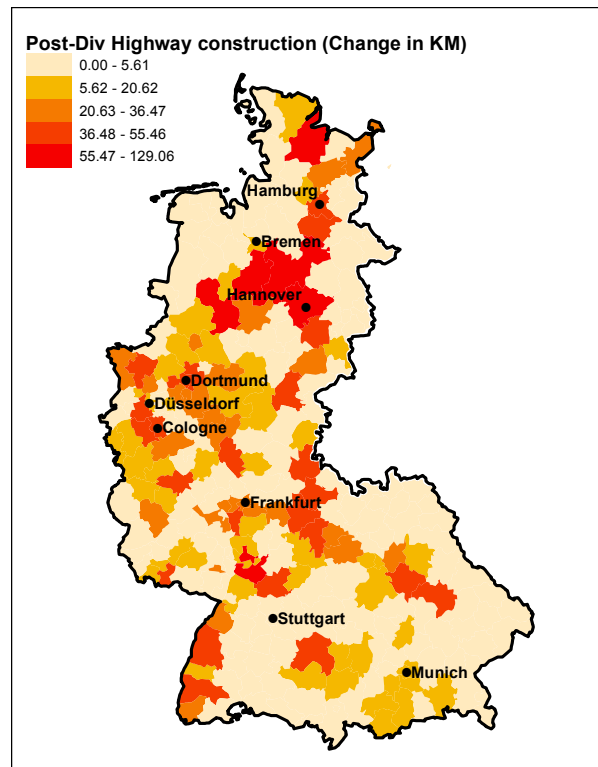
B) Outline Plan 1930

**Notes:** The shading represents the number of highway <sup>63</sup>kilometres by district (darker, more kilometres). The upper panel displays the highway kilometres predicted by the model while the lower panel displays the highway kilometres allocated to each district in the Highway Plan of 1930.

FIGURE V: Simulated Infrastructure investments after the division shock



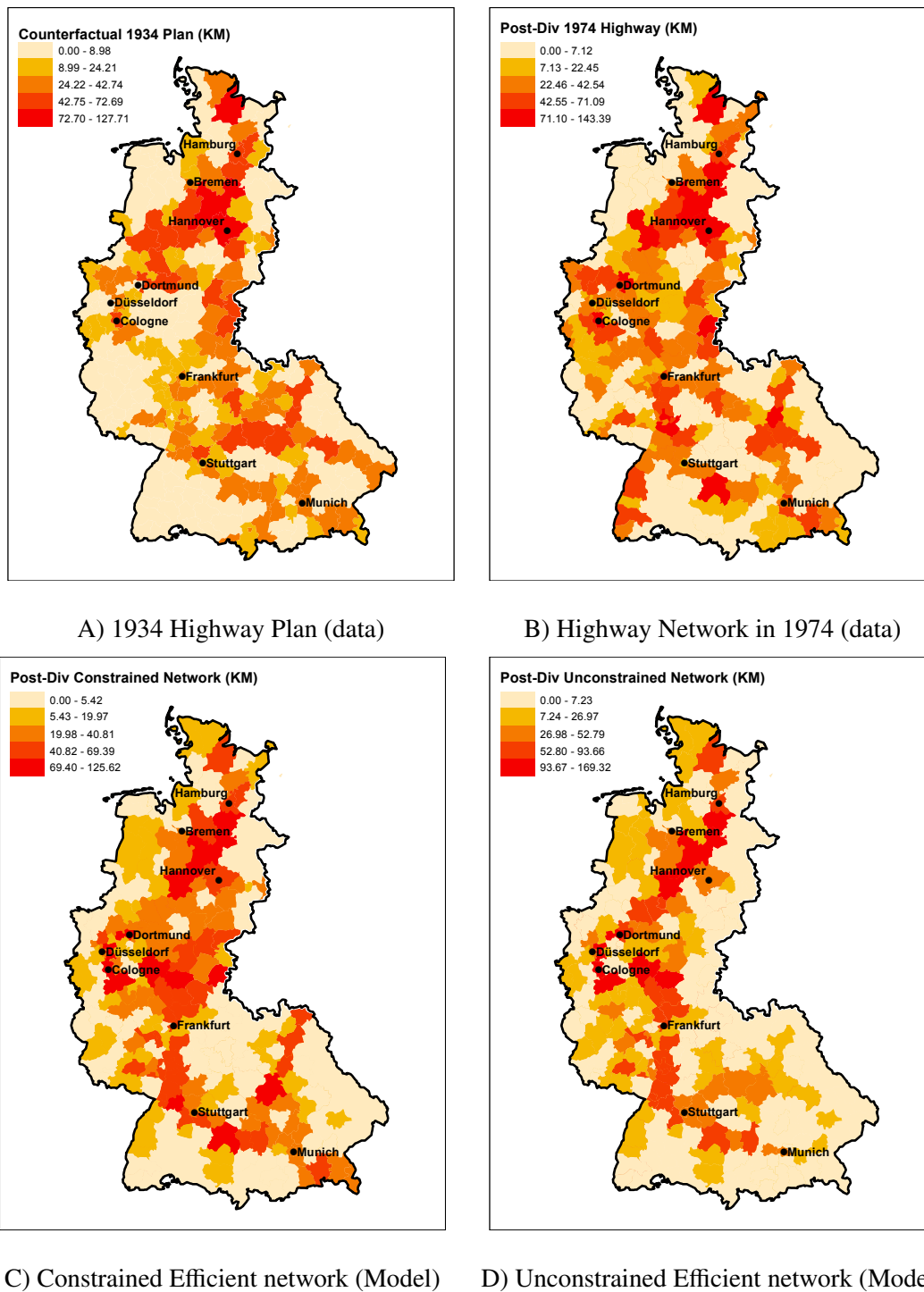
A) Model



B) Highway network (1974-1950)

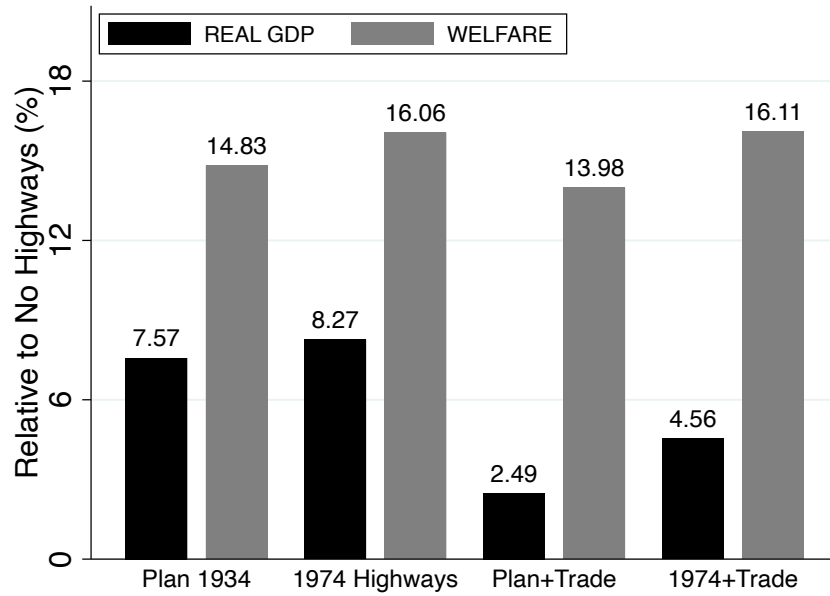
**Notes:** The shading represents the change in highway <sup>64</sup>kilometres by district (darker, more kilometres). The upper panel displays the change in kilometers predicted by the model while the lower panel displays the change in kilometers observed in the data (between 1950 and 1974).

FIGURE VI: Infrastructure investments in the historical data and model-based networks



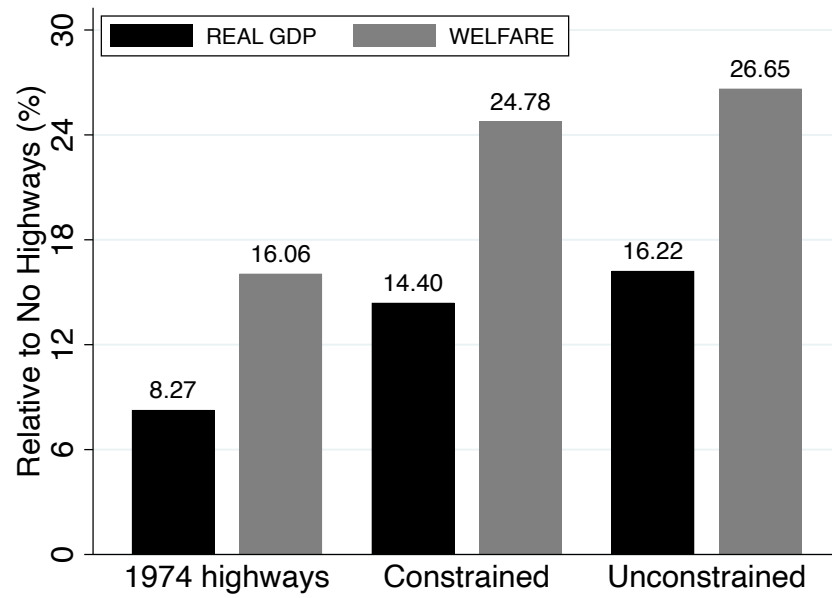
**Notes:** The shading represents the change in investment allocation by district. The shades represent the number of kilometres, darker shades meaning larger investments. Panel A shows the allocation designed under the 1934 Highway Plan while panel B the allocation under the actual 1974 highways network. Panel C shows the allocation predicted by the model when taking as given investments before division and panel D the allocation assuming no investments before division.

FIGURE VII: Gains from partial-reshaping post-division



**Notes:** Gains in welfare and real income from two alternative highway allocations: the 1934 highway Plan and the actual highway network in 1974. Two scenarios considered: the closed-economy model (bars 1-4) and the open-economy model (bars 5-8), that allows trade with Western Europe. The gains are measured as a percentage of the welfare and real income level in an economy with zero kilometres of highways built.

FIGURE VIII: Economic costs of path-dependence in infrastructure



**Notes:** Gains in welfare and real income from two alternative highway allocations: the constrained allocation case (pre-division highways taken as given in the solution) and the unconstrained allocation case (no pre-division highways taken as given). The gains are measured as a percentage of the welfare and real income level in the economy under the assumption of having zero kilometres of highways built.

# RESHAPING INFRASTRUCTURE: EVIDENCE FROM THE DIVISION OF GERMANY

SUPPLEMENTARY APPENDIX (For online publication only)

Marta Santamaria (University of Warwick)

## A THEORETICAL APPENDIX

### I A MODEL OF TRADE WITH ENDOGENOUS INFRASTRUCTURE INVESTMENTS

In this section I describe in detail the model presented in section III. The model features costly trade across many domestic districts,  $i = 1 \dots N$ , endowed with an exogenous productivity,  $A_i$ . There is a measure  $L$  of workers that move across districts according to their own heterogenous preferences. This model builds on the family of widely used quantitative spatial models reviewed by Redding and Rossi-Hansberg (2017) and is specially close to Redding (2016).

**Preferences** The preferences of each worker are given by three components. First, a heterogenous preference taste ( $b$ ), that represents how much a given worker values a given location (Redding (2016)). Second, a consumption component ( $C$ ) that can be represented by a canonical CES demand system, with every agent choosing the level of consumption of each of the varieties available with a constant elasticity of substitution across varieties of  $\sigma$ . Finally, a housing bundle,  $H_n$ . Specifically, the utility function of an agent  $\omega$  living in district  $n$  is given by:

$$U_n = b_n(\omega) \left( \frac{C_n}{\alpha} \right)^\alpha \left( \frac{H_n}{1 - \alpha} \right)^{1-\alpha} \quad (33)$$

where  $C_n = \left[ \sum_i^N \int_0^{M_i} c_{ni}(v)^{\frac{\sigma-1}{\sigma}} dv \right]^{\frac{\sigma}{\sigma-1}}$ , is the consumption basket chosen by workers living in district  $n$ ,  $c_{jn}(v)$  is the consumption of a worker that lives in district  $n$  of variety  $v$  produced in district  $j$ <sup>63</sup>.  $M_i$  is the number of available varieties produced in location  $i$ . The taste component  $b_n(\omega)$  is an idiosyncratic taste preference. Each worker draws a vector of  $N$  realisations  $\{b_n(\omega)\}_{n=1 \dots N}$  from a

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<sup>63</sup>Notice that workers living in  $n$  face the same consumption prices and earn the same wage so they make the same consumption choices

Frechet distribution that governs the individual preferences for each district:

$$G_n(b) = [Pr(b_n(\omega) \leq b)] = e^{-b^{-\epsilon}} \quad (34)$$

where  $\epsilon$  is the shape parameter governing the dispersion of tastes across workers for each location.

A large  $\epsilon$  implies a low dispersion (low standard deviation). Less dispersion means that the idiosyncratic preferences are more equal across districts for all workers. In this case a small difference across districts will trigger big movements in population. In the limit,  $\epsilon \rightarrow \infty$  all workers behave identically. They become indifferent between locations and the model collapses to the *perfectly mobile labour* case because all districts are perceived as equally desirable and tiny changes in wages trigger large population reallocations. When  $\epsilon \rightarrow 1$ , highest dispersion, workers are very heterogeneous in their taste. This means that large differences in district-level outcomes are needed to make workers move from their preferred choices. In this type of models the labour supply in a district is upward sloping in the wage.

**Production** Production uses labour as only factor of production, happens within firms and takes the form of monopolistic competition. There is a fixed cost to pay to start production,  $F$ , but once a firm enters the market it will produce a differentiated variety. The existence of the fixed cost and free entry ensures that each variety will only be produced by one firm. This means that each district will produce a specific and unique set of varieties that will equal the sum of varieties produced by the firms in that district. All varieties are produced with the same technology that is district-specific,  $A_i$ . From the firm's profit maximisation we know that a firm producing a variety  $\nu$  in location  $i$  will set a price  $p_i = \mu \frac{w_i}{A_i}$  where  $\mu$  is the mark-up charged over the price  $\mu = \frac{\sigma}{\sigma-1}$ . Notice that the price is constant across varieties produced in the same district. As we can see, each agent in the economy is endowed with one unit of labor that is supplied inelastically to produce  $A_i$  units of the district-specific varieties. I assume there is only one sector in the whole economy. The existence of free entry in each location drives down profits to zero and will pin-down the size of a firm in each



district:

$$q_i^F(v) = \frac{F * A_i}{(\mu - 1)} = A_i(\sigma - 1)F \quad (35)$$

As we can see more productive districts will have larger firms because they will be able to cover the fixed cost more easily. Given the scale of each firm and the local labour supply, the labour market clearing condition pins down the number of varieties (equal the number of firms) in each district:

$$M_i = \frac{L_i}{\sigma F} \quad (36)$$

Again, we see that larger districts will produce a larger number of varieties. Therefore, the productivity of a district determines the scale of its firms and the size of a district determines the number of varieties locally produced. Finally, we can re-write the optimal price index of tradables  $P_i$  in terms of the local price and the number of varieties produced in each district, taking into account that all varieties in a given location have the same price and substituting the number of varieties in each district:

$$P_n = \frac{1}{\sigma F} \left[ \sum_j^N L_j p_{nj}^{1-\sigma} \right]^{\frac{1}{(1-\sigma)}} \quad (37)$$

The price index in a district will depend on the local prices of imported varieties with larger regions exporting a larger share and therefore having a higher weight on the price index.

**Location and Consumption choices** Given the specification of preferences, we can write the indirect utility function of worker  $\omega$  in district  $n$  as

$$U_{n,\omega} = \frac{b_n(\omega)w_n}{P_n^\alpha r_n^{1-\alpha}} \quad (38)$$

Since indirect utility is a monotonic function of the idiosyncratic preference draw, it has a Frechet distribution too:

$$G_n(U) = Pr[U_n \leq u] = e^{-\Psi_n U^{-\epsilon}} \quad (39)$$

where  $\Psi_n = (\frac{v_n}{P_n})^\epsilon$ .  $G_n(u)$  is the distribution of indirect utility realisations in district  $n$ .

Each worker chooses the location that maximises her indirect utility. Using the properties of the Frechet distribution we find that the probability that a worker chooses to live in district  $n$ :

$$\pi_n = Pr[U_n \geq \max\{U_s; s \neq n\}] = \int_0^1 \underbrace{\prod_{s \neq n} [1 - G_n(U)]}_{Pr(U_s < u), s \neq i} \underbrace{dG_n(U)}_{cdf U_n} = \frac{(\frac{w_n}{P_n})^\epsilon}{\sum_k (\frac{w_k}{P_k})^\epsilon} \quad (40)$$

The fraction of workers that choose to live in district  $n$  coincides with the probability that any given worker chooses  $n$ :

$$L_n = \frac{(\frac{w_n}{P_n})^\epsilon}{\sum_{k=1}^N (w_k/P_k)^\epsilon} L \quad (41)$$

As we can see  $\epsilon$  is the elasticity of the labour share in any district to changes in real income income in that district  $w_n/P_n$ . Workers are more likely to choose districts with a relatively high real income.

Consumption is determined by the CES preference structure over varieties. The demand for variety  $v$  produced in district  $i$  and consumed in district  $n$  is:

$$x_{n,i}(v) = \frac{p_{n,i}^{1-\sigma}}{P_n^{1-\sigma}} w_n L_n \quad (42)$$

where  $P_n = \frac{1}{\sigma F} (\sum_k L_k p_{n,k}^{1-\sigma})^{1/(1-\sigma)}$  is the price index of consumption goods in district  $n$  and  $w_n L_n$  is the total expenditure in district  $n$ . Because each district produces a different set of varieties, the demand in district  $n$  for goods produced in district  $i$  (import share) will be:

$$X_{n,i} = \frac{L_i}{\sigma F} \frac{p_{n,i}^{1-\sigma}}{P_n^{1-\sigma}} w_n L_n \quad (43)$$

A district will import less goods from more expensive destinations (high  $p_i$ ) and will import more goods from other districts, relative to domestic consumption, if it is more expensive (has a high Price index  $P_n$ ). The above expression displays the Home market effect from the Krugman (1980) model: A larger district (high population) will produced a larger share of varieties and therefore

export larger shares to other districts (notice that trade share  $X_{in}$  is increasing in  $L_n$ ).

Finally, applying the same steps as before, we can compute the expected utility for each worker ex ante that is equal to the utility of the economy as a whole, ex post:

$$E(U_{n,\omega}) = \Gamma\left(\frac{\epsilon}{\epsilon-1}\right) \left( \sum_1^N (w_n / (P_n^\alpha r_n^{1-\alpha}))^\epsilon \right)^{1/\epsilon} \quad (44)$$

## II EXISTENCE AND UNIQUENESS OF THE SPATIAL EQUILIBRIUM

We can use the expected utility equation (44), the equilibrium conditions in the goods market (11) and land market residential (13), the goods price index equation (12) and the location choice probabilities (14) to write the common level utility across all districts in terms of the fundamentals and population of a give location  $n$  as:

$$\bar{U} = \frac{\delta A_n^\alpha \left(\frac{1}{\pi_{nn}}\right)^{\frac{\alpha}{\sigma-1}} H_n^{1-\alpha} L_n^{-\left(\frac{1}{\epsilon} + (1-\alpha) - \frac{\alpha}{\sigma-1}\right)}}{\alpha \left(\frac{1-\alpha}{\alpha}\right)^{1-\alpha} \left(\frac{\sigma}{\sigma-1}\right)^\alpha (\sigma F)^{\frac{\alpha}{\sigma-1}} (\bar{L})^{-\frac{1}{\epsilon}}} \quad (45)$$

Thus, the elasticity of welfare in one location to population in that location is given by the exponent of  $L_n$  in the above formula. Following Allen and Arkolakis (2014) and Redding (2016), given the land area  $\{H_n\}$ , productivity parameters  $\{A_n\}$  and quasi-symmetric bilateral trade frictions, there exists a unique and stable spatial equilibrium if

$$\left( \frac{1}{\sigma-1} - \frac{1}{\alpha\epsilon} - \frac{(1-\alpha)}{\alpha} \right) \leq 0, \quad (46)$$

which coincides with the welfare to labour elasticity and is fulfilled when the dispersion forces are as least as strong as the agglomeration forces in the economy.

### III GOVERNMENT'S PROBLEM

We can write the problem of the Government as follows:

$$\text{Max}_{\{\phi_k\}} \delta \left[ \sum_{n=1}^N (v_n(\Phi)/P_n(\Phi)^\alpha r_n(\Phi)^{1-\alpha})^\epsilon \right]^{1/\epsilon},$$

subject to:

#### 1. Goods market clearing

$$w_n L_n = \sum_i \frac{L_n}{\sigma F} \left( \frac{\sigma}{\sigma-1} \frac{w_n}{A_n} T_{n,i}(\Phi) \right)^{1-\sigma} P_i^{\sigma-1} w_i L_i, \forall i, n. \quad (48)$$

#### 2. Labour market clearing

$$\frac{L_n}{L} = \frac{(w_n/P_n^\alpha r_n^{1-\alpha})^\epsilon}{\sum_{i=1}^N (w_i/P_i^\alpha r_i^{1-\alpha})^\epsilon} \text{ and } \sum_i L_i = \bar{L}, \forall i, n. \quad (49)$$

#### 3. Least-cost path shipping

$$\text{argmin } T_{n,i}(\Phi) = \{\mathbb{I}_{n,i}\}, \forall i, n. \quad (50)$$

#### 4. Government's budget constraint

$$\sum_n c_k \phi_n \leq Z, \quad (51)$$

where  $P_i = \left[ \sum_m \frac{L_m}{\sigma F} \left( \frac{\sigma}{\sigma-1} \frac{w_m}{A_m} T_{i,m} \right)^{1-\sigma} \right]^{1/(1-\sigma)}$ ,  $r_i = \left( \frac{1-\alpha}{\alpha} \right) \frac{w_i}{L_i}$  and  $\delta = \Gamma(\frac{\epsilon}{\epsilon-1})$ , where  $\Gamma$  is the gamma function.

The Lagrangian associated to this problem is

$$\begin{aligned} \mathcal{L} : & \delta \left[ \sum_{n=1}^N (v_n / P_n^\alpha r_n^{1-\alpha})^\epsilon \right]^{1/\epsilon} - \sum_{n=1}^N \eta_n \left( w_n L_n - \sum_i \frac{L_n}{\sigma F} \left( \frac{\sigma}{\sigma-1} \frac{w_n}{A_n} T_{n,i} \right)^{1-\sigma} P_i^{\sigma-1} w_i L_i \right) \\ & - \sum_{n=1}^N \lambda_n \left( \frac{L_n}{L} - \frac{(w_n / P_n^\alpha r_n^{1-\alpha})^\epsilon}{\sum_{i=1}^N (w_i / P_i^\alpha r_i^{1-\alpha})^\epsilon} \right) - \sum_n \sum_i m_{n,i} (\{\Pi_{j,i}\} - \{\mathbb{I}_{n,i}\}) - \kappa \sum_n (L_n - \bar{L}) - \mu \left( \sum_n c \phi_n - Z \right) = 0, \end{aligned} \quad (52)$$

where  $\{\eta_n\}$ ,  $\{\lambda_n\}$ ,  $\{m_{in}\}$ ,  $\kappa$  and  $\mu$  are the lagrangian multipliers associated with the problem's constraints for the full problem.

To build some intuition, consider now a simplified version without housing ( $\alpha = 1$ ) and where the least-cost path vectors  $\{\mathbb{I}_{n,i}\}$  are fixed, so that changes in infrastructure quality do not affect the optimal path to ship goods. The associated Lagrangian is then:

$$\begin{aligned} \mathcal{L} : & \delta \left[ \sum_{n=1}^N (v_n / P_n)^\epsilon \right]^{1/\epsilon} - \sum_{n=1}^N \eta_n \left( w_n L_n - \sum_i \frac{L_n}{\sigma F} \left( \frac{\sigma}{\sigma-1} \frac{w_n}{A_n} T_{n,i} \right)^{1-\sigma} P_i^{\sigma-1} w_i L_i \right) \\ & - \sum_{n=1}^N \lambda_n \left( \frac{L_n}{L} - \frac{(w_n / P_n)^\epsilon}{\sum_{i=1}^N (w_i / P_i)^\epsilon} \right) - \kappa \sum_n (L_n - \bar{L}) - \mu \left( \sum_n c \phi_n - Z \right) = 0. \end{aligned} \quad (53)$$

The FOC with respect to  $\phi_k$  is:

$$\frac{\partial \mathcal{L}}{\partial \phi_k} = 0 : \underbrace{C \left[ \sum_n U_n^{(\epsilon-1)} \frac{\partial U_n}{\partial \phi_k} \right]}_{\text{Direct effect}} + \underbrace{\sum_n \sum_i \eta_n \frac{\partial X_{n,i}}{\partial \phi_k}}_{\text{Response of wages}} + \underbrace{\sum_n \lambda_n \frac{\partial (L_n / L)}{\partial \phi_k}}_{\text{Response of Labour}} = \underbrace{\mu c}_{\text{Marginal cost}}, \quad (54)$$

where  $C = \delta \left[ \sum_n U_n^\epsilon \right]^{\frac{1}{\epsilon}-1}$  is constant across all locations and  $U_n = (v_n / P_n)$  is indirect utility in location n. As we can see, there is a direct effect of the change in infrastructure on indirect utility, that works through the change in transport costs and prices at destination, and an indirect effect (general equilibrium) that works through the adjustment of wages in the goods market and the relocation of population in the residential market. To get a sense of the direct effects, let us assume

the indirect effects are small so that we can ignore them. We can re-write the direct effect as :

$$\begin{aligned}
\mu c &= C \sum_n^N U_n^{(\epsilon-1)} \left[ \sum_i^N \frac{\partial U_n}{\partial p_{n,i}} \times \frac{\partial p_{n,i}}{\partial \phi_k} \right], \\
&= C \sum_n^N U_n^{(\epsilon-1)} \left[ \sum_i^N \frac{\partial U_n}{\partial p_{n,i}} \times p_i \frac{\partial T_{n,i}}{\partial \phi_k} \right], \\
&= C \sum_n^N U_n^{(\epsilon-1)} \left[ \sum_i^N \frac{\partial U_n}{\partial p_{n,i}} \times p_i \left( \sum_x^V \mathbb{I}_{n,i}^{x,k} (-\gamma) \frac{d_{x,k}}{\phi_k^{\gamma+1}} \right) \right], \\
&= C \sum_n^N U_n^{(\epsilon-1)} \left[ \sum_m^N \left( -\frac{1}{P_n} \frac{X_{n,i}}{p_{n,i}} p_i \left( \sum_x^V \mathbb{I}_{n,i}^{x,k} (-\gamma) \frac{d_{x,k}}{\phi_k^{\gamma+1}} \right) \right) \right],
\end{aligned} \tag{55}$$

where the last line uses Roy's identity to replace  $\frac{\partial U_n}{\partial v_n} = -\frac{\partial U_n}{\partial v_n} \times q_{n,i}$  where  $q_{n,i}$  denotes de quantity of varieties produced in i and demanded in location n and  $v_n$  is disposable income in n. We replace  $\frac{\partial U_n}{\partial v_n} = \frac{1}{P_n}$  and  $q_{n,i} = \frac{X_{n,i}}{p_{n,i}}$ .

The effect of investing in infrastructure in location k ( $\phi_k$ ) on transport costs between regions n and i, is symmetric:  $\frac{\partial T_{n,i}}{\partial \phi_k} = \frac{\partial T_{i,n}}{\partial \phi_k} = \sum_x^V \mathbb{I}_{n,i}^{x,k} (-\gamma) \frac{d_{x,k}}{\phi_k^{\gamma+1}}$ . Infrastructure investments are location-specific and the combination of the investments at the endpoints of any edge is symmetric.

Rearranging the terms, we can further simplify equation 55 as:

$$\begin{aligned}
\mu c &= \frac{\gamma}{\phi_k^{\gamma+1}} C \sum_n^N U_n^{(\epsilon-1)} \left[ \sum_i^N (P_n^{-1} \frac{X_{n,i}}{T_{n,i}}) \left( \sum_x^V \mathbb{I}_{n,i}^{x,k} d_{x,k} \right) \right], \\
\phi_k^{\gamma+1} &= \frac{\gamma}{\mu c} C \sum_k^N \sum_n^N U_n^{(\epsilon-1)} (P_n^{-1} \frac{X_{n,i}}{T_{n,i}}) \left( \sum_x^V \mathbb{I}_{n,i}^{x,k} d_{x,k} \right).
\end{aligned} \tag{56}$$

Define function  $e(j, j') = \left[ \frac{U_j^{\epsilon-1}}{P_j} \frac{X_{j,j'}}{T_{j,j'}} \right]$ , increasing in expenditures of location j on goods from location j'. Then,

$$\begin{aligned}
\phi_k^{\gamma+1} &= \frac{\gamma}{\mu c} C \sum_n^N \sum_i^N e(n, i) \left( \sum_x^V \mathbb{I}_{n,i}^{x,k} d_{x,k} \right), \\
\phi_k^{\gamma+1} &= \frac{\gamma}{\mu c} C \left( \sum_n^N e(n, k) \sum_{N(k)} d_{x,k} + \sum_{n \neq k}^N \sum_{i \neq k}^N e(n, i) \sum_x^V \mathbb{I}_{n,i}^{x,k} d_{x,k} \right),
\end{aligned} \tag{57}$$

where  $N(k)$  denotes the vertices that are neighbours (adjacent) to k.

## B QUANTIFICATION APPENDIX

### I QUANTIFICATION OF THE MODEL BEFORE DIVISION

**Initial transport network** We have 3 types of roads in Germany in 1938: Highways, Federal Highways and Local roads. To construct the initial transport grid I choose the smallest set of edges and vertices that allows me to represent the underlying geography of Germany to transport goods. First I select the set of vertices to represent the 412 German districts I observe in the data. I choose as the vertex of the district the centroid of the path of any highways that transits the district. If there is no highway in the district I use the centroid of the federal highway inside the district. If there are no highways or federal highways I use the centroid of the local road. Second I build the set of edges that connects the vertices that represent the population centres. To do this I select all highways and federal highways that existed in 1938. I add the set of local roads needed to connect the remaining vertices that do not have highway access.<sup>64</sup>

Finally, I export the network to use in my quantitative analysis. TableB.1 summarises the features of the network. The network before division is composed of 1,633 nodes, collected into 412 districts, and 1,866 edges (links) that can be exported as two vectors: one containing the links and one containing the cost of transiting each link (called weight in the networks literature). The network after division, once we drop East German locations (nodes) and transport network (edges) is composed of 1,290 vertices and 1,463 nodes.

**Initial transport costs** To compute the initial transport cost matrix I follow [Combes and Lafourcade \(2005\)](#) transport cost function. The function is derived to account for the cost of shipping one truck full of goods in France in the decade of 1978. The transport cost specification for shipping a

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<sup>64</sup>To select this edges I choose the least cost path to connect each of the 57 districts that are not transited by a highway or a federal road to the closest district with federal highway using the "Closest facility Tool" in ArcGIS that allows you to extract the path chosen to connect facilities (federal highway points) to incidents (district centroids). Local roads are used as the default way to move around to prevent any transport costs to be zero. Instead of manually recovering the local road network in 1938 I use the 2004 digitised map of local roads and enable a truck to move through these links at 40 km per hour.

TABLE B.1: Transport Network graph

	Vertices	Edges	Length (km)
Pre-division	1,633	1,866	21,760
Post-division	1,290	1,463	14,442

**Notes:** Network built by author from actual road network in Germany as explained in the Supplementary Quantitative Appendix.

TABLE B.2: Cost of time and distance of truck shipping (France, 1978)

	Highway (Autobahn)	Federal Highway	Local road
Speed (km per hour)	80	60	40
Cost of distance (Euros)	85.8	89.8	97.18
Cost of time (Euros)	5.4	5.4	5.4

truck between  $i$  and  $n$  is:

$$t_{i,n} = \text{Distance cost} \times \frac{\text{speed}_{i,n}}{\text{length}_{i,n}} + \text{Time cost} \times \frac{\text{speed}_{i,n}}{\text{length}_{i,n}}. \quad (58)$$

The distance cost comes from the cost of oil/petrol (and other truck related maintenance costs) needed to drive the truck. The time cost comes from the wage that has to be paid to the driver. Both costs are recovered from

I compute cost of transit in each link using the above function and the actual kilometres. I use the least-cost path algorithm to compute the matrix of initial transport costs in euros. To convert this measure to ad-valorem quantities I normalise the computed cost in euros by 28,000 euros that is the average cost of a truck full of German goods in the year 1995. This computation uses the average export price per ton from Germany to France. This normalisation ensures that the transport cost matrix expresses the cost of shipping one unit of the average German good across any district pair in ad-valorem terms.



## II OPTIMAL INFRASTRUCTURE NETWORK

**Estimation of parameter  $\gamma$**  I estimate  $\gamma$  to match the skewness of investments in the 1934 highway plan. Skewness is a measure of the concentration of a distribution. Matching this moment ensures that the concentration of highway investments in the model is aligned with the data. To estimate  $\gamma$ , I use the distribution of investments across districts in relative terms (as shares of the budget) since I will calibrate the aggregate level of investments with the parameter of the budget,  $Z$ . To estimate the skewness of highway kilometres across districts in the data, I take 50 subsamples of sections of the 1934 highway Plan and compute the mean of the skewness of investments. Average skewness of the distribution of highway kilometres by district is 1.589.

I use the Simulated Method of Moments for the estimation. I simulate 100 times the optimal choice of infrastructure in a representative 50-district economy with 100 different random draws of the vector of district-specific productivities. I compute the skewness of these investments and estimate the value of  $\gamma$  that minimises the sum of squared differences between average skewness in the model and skewness in the data. For the simulation I specify the productivity distribution as a Pareto distribution with shape parameter  $\alpha_p = 1.6$ , estimated from the calibrated productivity distribution for Germany, scale parameter  $\sigma_p = 1$  and location parameter  $\theta_p = 0$ . This procedure yields an estimate of  $\gamma = 0.84$ , which yields a skewness of infrastructure investments of 1.819. Figure D.7 plots the histogram of simulated investments before the Division using the model (grey bars) over the histogram of the 1934 highway Plan investments taken from the data (white bars).

**Calibration of budget:  $Z^{pre}, Z^{post}$**  To calibrate the model's budget, I need a measure of the total transport costs reduction, as implied by the growth in trade flows within Germany. I use the growth in aggregate traffic flows by road within Germany between 1952 and 1974.

The evolution of domestic traffic flows by mode of transport is reported in table D.1. The growth of short-distance traffic by road, is four-fold between 1952 (503.3 Million Tons) and 1974 (2080.8 Million Tons). The increase of long-distance traffic of goods by road is four-fold as well in this

period. From 56.1 million tons to 224.1 million tons. However, not all of this increase can be attributed to the growth in highways, since the economy was booming in West Germany in these years. I therefore discount the growth rate of traffic by road, by the growth rate of traffic by railways. This is a good proxy of the economic growth rate and is independent of infrastructure improvements since the railway network remained fixed during this period. According to table D.1, traffic of goods by rail grew by 50%. To be conservative, I will calibrate the budget to generate a 3.2 times increase in traffic of goods rather than to a four-fold increase.

To fix the budget  $Z$  in the period after division, I want to find a measure in terms of ad-valorem transport costs that can generate a three-fold increase in trade by roads. The model I will then attribute this growth to the construction of around 5000 kilometres of highways. I use the gravity relationship implied by the model to fix the aggregate level of investment. Given the CES demand system and the elasticity of substitution=7, to generate a 3.2 times increase in aggregate trade flows we would need ad-valorem transport costs to be 46% lower ( $\Delta TC = -0.53\%$ ).

The shipping cost function between  $i$  and  $j$  depends on infrastructure investments as follows:

$$\omega_{ij} = \frac{d_{ij}}{0.5(\phi_i^\gamma + \phi_j^\gamma)} \quad (59)$$

A reduction of 55% along the  $(i,j)$  link, would be achieved by setting  $\phi_i = \phi_j = 2.5$ . On average, to achieve an overall reduction of 55% in transport costs we would need an investment of 780 units ( $2.5 \times 312$  districts) plus the lower bound investment to keep trade costs unchanged ( $\phi = 1$ ). Therefore, I set the post-division budget  $Z=1100$  ( $708+312$ ). For the pre-division investment I set a budget of  $Z= 1500$ , that is an increase of 30% to be allocated across 412 districts in East and West Germany.

Clearly, not all districts will be allocated 2.5 units of investment in the model's solution, but this level of aggregate investment could generate an increase in traffic as the one seen in the data. Alternatively, we could write the transport cost functions in kilometres rather than ad valorem units and calibrate the elasticity of trade to highway kilometres using the same traffic data.

### III OPTIMAL INFRASTRUCTURE NETWORK WITH INTERNATIONAL TRADE

To introduce international trade post-Division I consider trade with Belgium, France and Netherlands. I assume that trade with the rest of the world is only possible through the West German districts located in the border with these countries for which some highway had been designed in the prewar Highway Plan or for which some local road existed. In particular there are 11 districts in West Germany that are border regions with highways built by 1960 or planned (showing that some trade was likely to be taking place in the 1930s): six districts are at the border with the Netherlands, three districts are at the border with Belgium and four districts are at the border with France.

To model the new trading opportunities I choose to increase the population of the bordering regions with a share of the foreign population, so that access to these bordering regions allows a firm to sell products to the domestic population and to the foreign population as well. I assume that trade is possible with the whole population in the foreign countries but I compute a cost of trading with these foreign population equal to the average distance between the German border and the main foreign cities/capital city (for Belgium and Netherlands). I reduce the accessible population by a share to account for this distance cost. I take as example France. Taking into account the different border points in West Germany and the main cities in France, the distance that these shipments would have to cover is, on average, 500 kilometers. I use the 1938 parametrization of the model and compute the ad-valorem cost of shipping one unit over 500 km which is 1.6. To estimate how large would be the reduction in demand caused by this increase in price, we would need to estimate the elasticity of substitution between German and French (Belgian, Dutch) goods. Since this goes beyond the scope of this paper, I set this elasticity at  $\sigma^{row}=3$  following the trade literature (a value of between 4 and 8 has been found) and I use the lower end since the trade elasticity has increased from around 2-3 to around 8 in the last decades (Klasing et al., 2016).

Therefore, an increase in the price to 1.6 production price at a trade elasticity of -2 ( $1 - \sigma^{row}$ ) would imply a fall in demand to 40%.

Due to the lack of regional trade data in Europe for the 1960s, I use the same parametrization for all countries. Since Netherlands and Belgium are slightly closer by, I assume that the German exporters can reach half of the population of France, Belgium and Netherlands.<sup>65</sup> The population of these countries at the time is France 41,879,607 inhabitants, Netherlands 10,027,047 inhabitants and Belgium, 8,628,489 inhabitants.

I increase the population of each district mentioned above by an equal fraction of 0.5\* total population of the country with which it shares a border. For example, each of the six districts on the border with Netherlands will now have an increased population of 800,000 inhabitants.

This simplifying assumption of considering trade opportunities as an increase in the size of regions at the border allows me to follow the same calibration strategy as before: I re-calibrate the productivity vector to match the new population distribution where the bordering regions have been allocated extra population coming from the foreign countries. The rest of the calibration procedure is the same as described previously.

## IV COUNTERFACTUAL EXERCISES

**Taking the highway network to the model** To construct the model counterpart of the 1974 highway allocation I follow two steps. First, I compute the district share of highway kilometres. This is obtained by dividing the total highway kilometres in a district by the total highway kilometres built in 1974 in West Germany. Then, I multiply the highway share by the total budget allocated in the model to the Post-Division network, as follows:

$$\phi_i = 1 + share_{i,74} * (Z - 312), \quad (60)$$

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<sup>65</sup>A more sophisticated calibration would be possible but the lack of regional data or shipments across borders in 1950 or 1960 will not allow us to test the performance of the calibration. Given this, I choose simplicity but robustness checks could be run to provide different bounds.

where I subtract 312 from  $Z$  because that is the lower bound imposed by the requirement that highway investments cannot increase the transport costs and

$$share_{i,74} = \frac{\text{Highway km}_{i,1974}}{\sum_i^N \text{Highway km}_{i,1974}}. \quad (61)$$

In the same way, I build the counterpart of the 1934 plan as

$$\phi_i = 1 + share_{i,Plan} * (Z - 312), \quad (62)$$

## C DATA APPENDIX

**Highway data** The highway network data (Autobahns) collected for the empirical exercise is of two types. First, I digitise the highway network plan of 1934 from historical documents. From the digitised data I construct a district level measure of the number of kilometres that the 1934 highway plan allocated to each district. Besides, I collect data of the actual highway network (only Autobahn) in Germany (both East and West Germany) for the years 1938, 1950, 1965, 1974, 1980 and 1989. This information is obtained from different road atlases and historical maps and geo-referenced using the software ArcGIS. Once the maps and atlases are digitised I manually collect the data to construct the highway network in each period.

Additionally, I collect and geo-reference the pattern of federal roads in 1950 and 1965. Federal roads (Bundesstrasse) are decided by the central government but are not restricted-access roads like the Autobahns and the network was developed earlier than the highway network.

Finally, the network of local roads is imported from the EuroGlobal map by *Eurographics* that provides harmonised European open geographical data covering 45 countries and territories in the European region and is freely available. The website address of Eurographics is <https://eurogeographics.org>.

**Economic outcomes** As economic outcomes, I use population data by decade at the district level from the historical census.

Additionally, I collect traffic of goods by road for 18 aggregated traffic districts in Germany. The traffic data is collected in tons and reported in an aggregated way (Total tons of goods sent to the rest of Germany and received from Germany). The traffic data is collected from the "Statistisches Jahrbuch fr das Deutsche Reich". I use data from the year 1938, the closest to the beginning of the construction of the highway network. The scanned photocopies of the annual editions of the "Statistisches Jahrbuch fr das Deutsche Reich" are available at <http://www.digizeitschriften.de/dms/toc/?PID=PPN514401303>.

Finally, I collect and digitise traffic of goods by road between West German states. This data is available only after 1960 (most recent data I found was 1966). The traffic data is collected in tons and reported in an aggregated way (Total tons of goods sent to each state and received from each state in West Germany). This traffic data is collected and digitised from the "West Germany Road freight transport 1945- Statistics Serials" (Der Fernverkehr mit Lastkraftfahrzeugen: Zusammengefasste bersichten zur Gterbewegung).

**Geographic variables** As controls, I collect a series of measures related to the geography of Germany such as area of districts and distance to relevant points such as the inner German border. First, I measure the distance from each district to the closest point of the inner German border, to the closest point to the external West German border and West Berlin. I calculate these distances from the centre of each district to the geographic feature of interest over a straight line. Furthermore, I compute the distance to West Berlin through the transport network in 1950. Finally, I collect the district area in square kilometres.

## D SUPPLEMENTARY TABLES AND FIGURES

TABLE D.1: Traffic flows by transport mode

Mode	Year			
	1952	1962	1968	1974
Railway	262.0	329.2	366.4	404.2
Trucks: Long-distance	56.1	109.8	192.9	224.6
Trucks: Local traffic	503.3	1280.7	2025.8	2080.8

**Notes:** Values in Millions of Tons, for West Germany. Collected by author from the Statistical Yearbook of the German Republic, multiple years.

TABLE D.2: Elasticity of trade flows to distance

Outcome: Log (Road shipments in tons)	(1)	(2)
	DATA 1938	MODEL ( $\sigma = 7$ )
Log(Distance)	-2.8674*** (0.2381)	-2.7808*** (0.3762)
Constant	28.7349*** (1.4651)	35.9057*** (2.3151)
Observations	13	13
$R^2$	0.929	0.832

\*  $p < 0.10$ , \*\*  $p < 0.05$ , \*\*\*  $p < 0.01$

**Notes:** Standard errors, are in parentheses. Regression run using total tons shipped by truck by manufacturing firms over 13 distance brackets ( from less than 50km to more than 1000km). Model regression using simulated trade data given parameter values and infrastructure in 1938 aggregated over the same distance brackets



TABLE D.3: Choice of Parameters

Parameter	Description	Source/Target	Value
<b>From Literature</b>			
$\varepsilon$	Shape parameter of Fréchet	Monte et al. (2015)	3
$\alpha$	Share of tradables	Redding, Sturm (2008)	0.7
<b>1938 Germany</b>			
$\{A_i\}$	Productivity parameter	Match population 1938	
$\{H_i\}$	Land supply	Area in sqkm	
$\sigma$	Elasticity of substitution	Trade elasticity 1938	7
<b>Infrastructure</b>			
$\gamma$	Returns to highway investments	Concentration in 1934 Plan	0.84
$Z$	Budget of Government	Trade volume post-division	1100-1500
$c$	Marginal cost	-	1

**Notes:** Further details about the calibration and estimation of the parameters can be found in section IV in the main text and in section B of this Appendix.

TABLE D.4: Model Validity Test: Change in Population distribution - First Stage results

Dependent Var:	$\Delta \ln \text{Market Access (1974,1938)}$
	(1)
$\Delta \ln \text{Market Access (Plan,1938)}$	0.744*** (0.039)
Dist2border	0.001*** (0.000)
Constant	-0.014 (0.044)
State FEs	Yes
Observations	312
$R^2$	0.636
F test	47.7

TABLE D.5: Model Validity Test: Change in Population distribution 1950 to 1980

Dependent Var.:	$\Delta \ln \text{Population}_i^{80,50}(\text{DATA})$		
	OLS	OLS	IV
mod	(1)	(2)	(3)
$\Delta \ln \text{Market Access}(1950,1938)$	0.480*** (0.135)		
$\Delta \ln \text{Market Access}(1974,1938)$		0.182*** (0.029)	0.235*** (0.073)
Dist2border		0.001*** (0.000)	0.001*** (0.000)
Constant	0.386*** (0.014)	0.057 (0.054)	0.035 (0.059)
State FEs	Yes	Yes	Yes
Observations	312	312	312
$R^2$	0.251	0.282	0.280

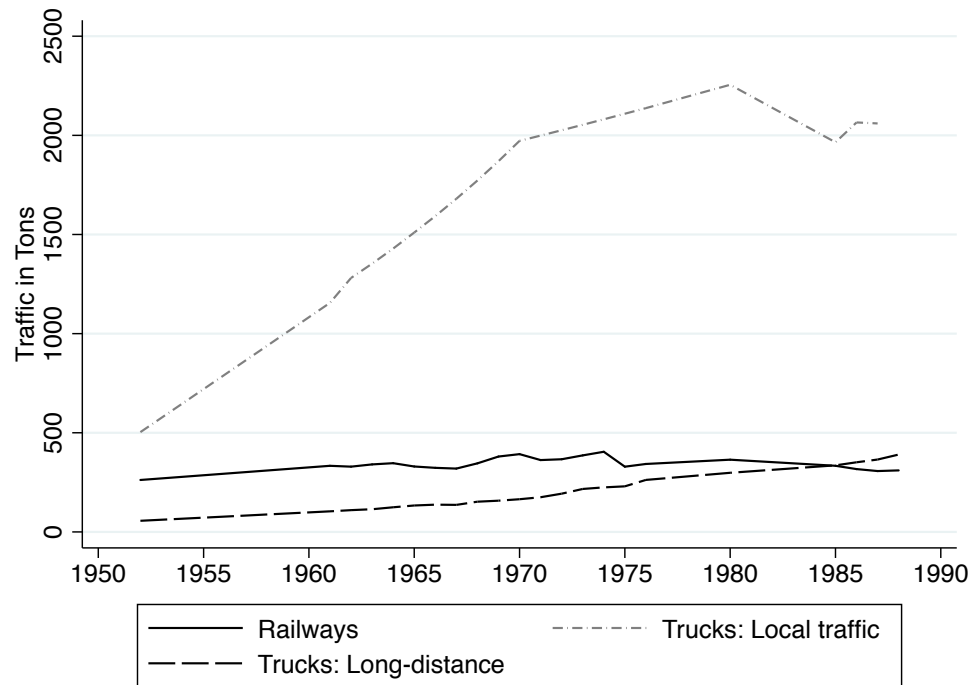
**Notes:** Standard errors clustered at the Government-region level in parentheses.\* significant at 10%, \*\* significant at 5%, \*\*\* significant at 1%.

TABLE D.6: Model Validity test- Infrastructure investments

Dep Variable	POST: Baseline		POST: Int. Trade
	$\Delta T_{i,j}(1974 - 1949)$	$\Delta T_{i,j}(1974 - 1949)$	$\Delta T_{i,j}(1974 - 1949)$
	(1)	(2)	(3)
$\Delta$ Transport Costs (Model baseline)	0.7368*** (0.0004)		
$\Delta$ Transport Costs (1934 Plan)		0.9768*** (0.0008)	
$\Delta$ Transport Costs (Model extended w/ trade)			0.7457*** (0.0004)
Constant	-0.0384*** (0.0006)	-0.0746*** (0.0009)	-0.0394*** (0.0006)
Observations	96721	96721	96721
$R^2$	0.970	0.923	0.968
Mean dep. var	-0.78	-1	
SD dep. var	0.42	0.57	

Notes: Standard errors, are in parentheses.\* significant at 10%, \*\* significant at 5%, \*\*\* significant at 1%.

FIGURE D.1: Goods traffic by transport mode



Note: Values are for West Germany, collected by author from Statistical Yearbook of the Bundesrepublik, multiple years. Values for missing years are interpolated.

FIGURE D.2: 1930s Highway Plan (HAFRABA outline)

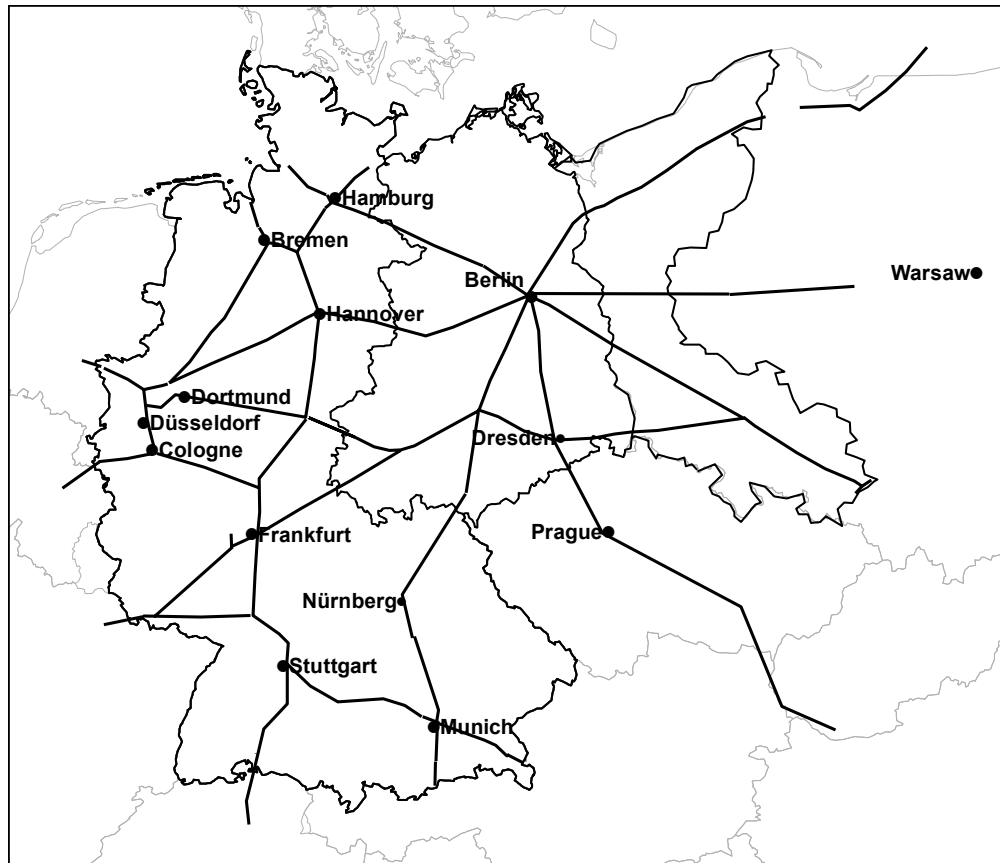


FIGURE D.3: 1934 Highway Plan (Fritz Todt)

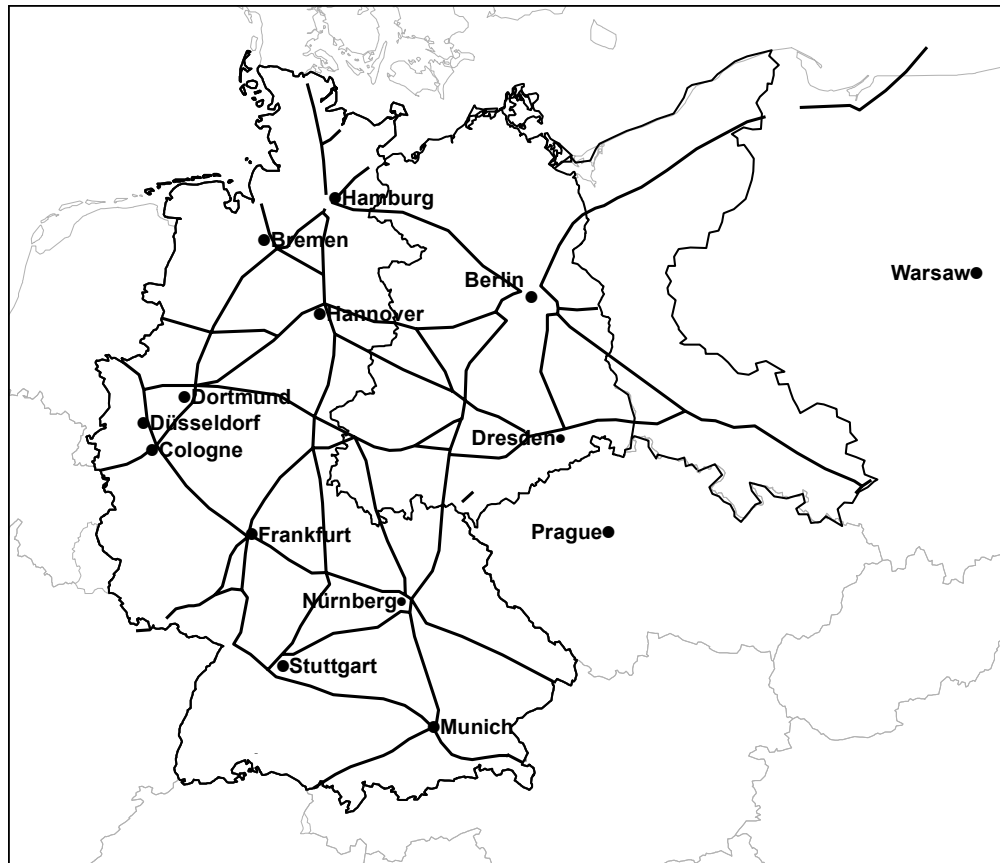
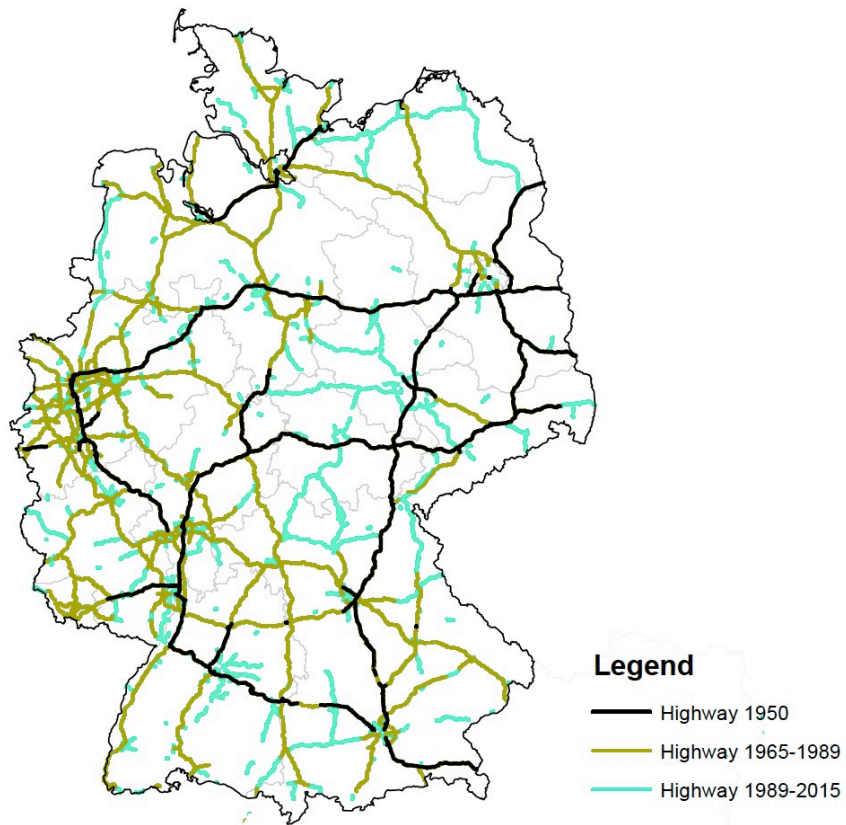


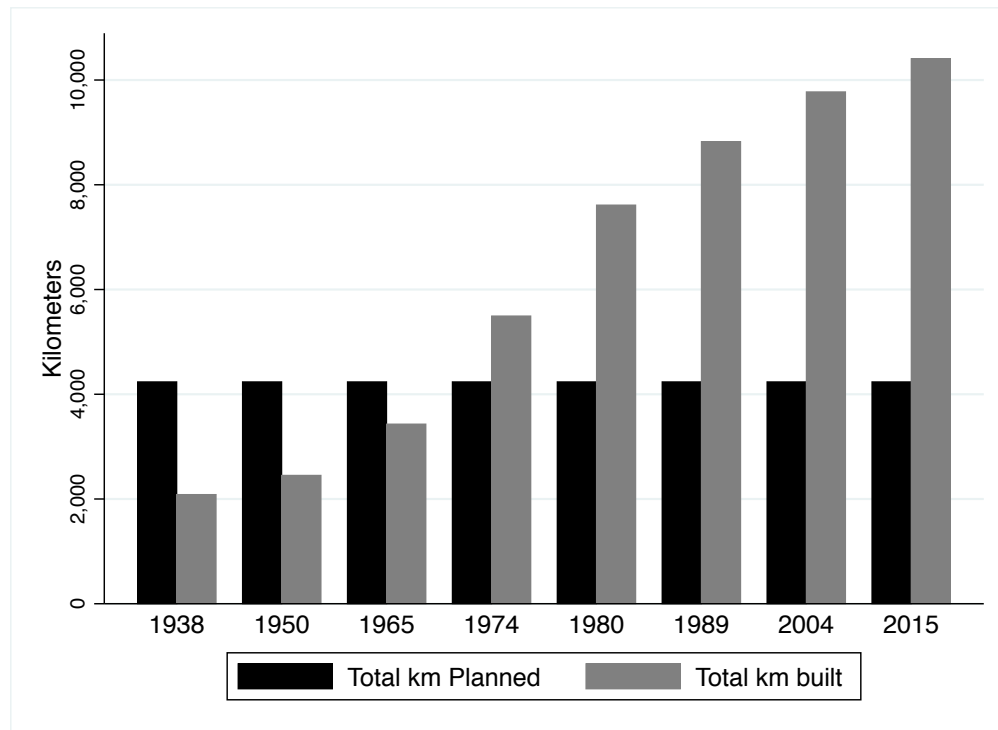
FIGURE D.4: Evolution of the German highway network



**Notes:** German highway data collected from Michelin Atlases of the years 1950, 1964, 1975, 1980 and 1989 digitised by the author.

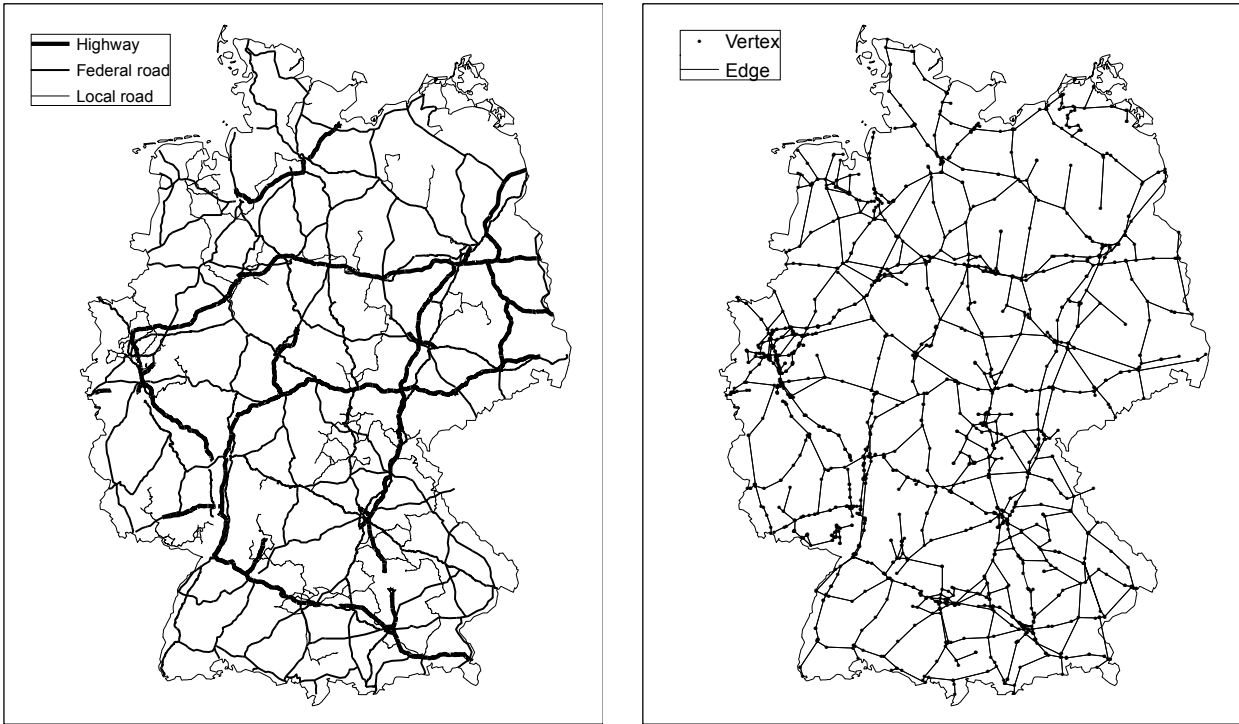


FIGURE D.5: Construction and Planning of the Highway Network in West Germany



**Notes:** Total kilometres scheduled to be built in West Germany in the 1934 Highway Plan (black bars) and actual kilometres completed (grey bars).

FIGURE D.6: Representative transport network and corresponding graph

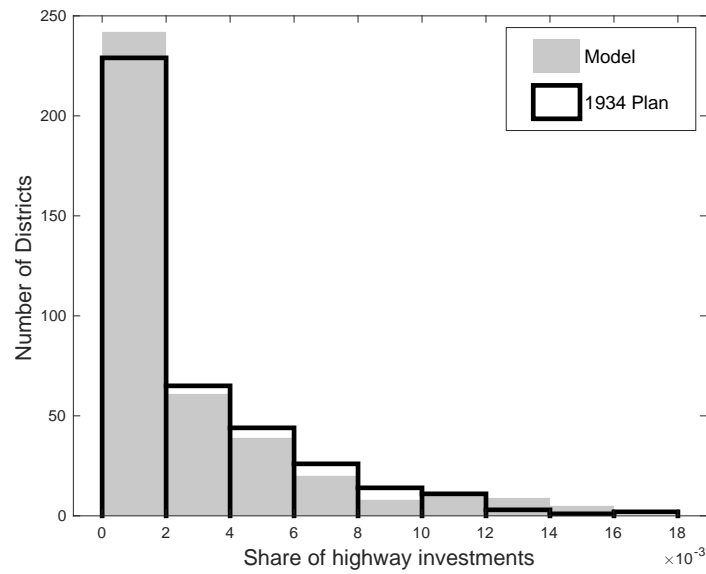


**A) Chosen network**

**B) Graph**

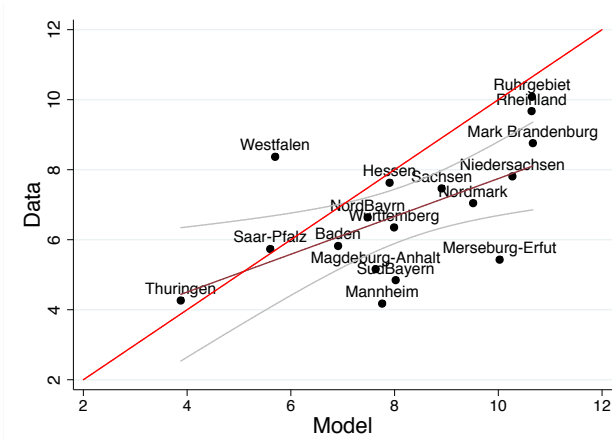
**Notes:** Panel A shows the roads that I choose to build the grid. This network connects all districts while the number of links remains small. Highways are the darkest lines, federal highways are the intermediate lines, and local roads are the thinnest lines. Panel B shows the discretisation of the network in panel A. Each dot represents a vertex, and each line represents an edge of the network.

FIGURE D.7: Distribution of investment shares by district: Model vs Data

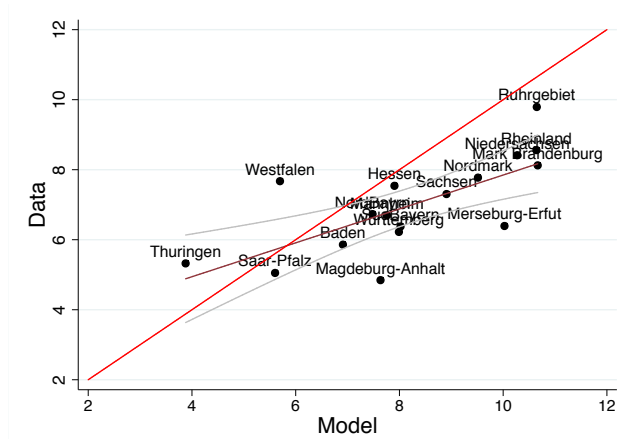


**Notes:** The figure plots the share of the total budget allocated by district in the model, solution for pre-division period, (in grey) and the share of the total length of the 1934 Plan allocated to each district (in white).

FIGURE D.8: Model fit before Division - Domestic Trade



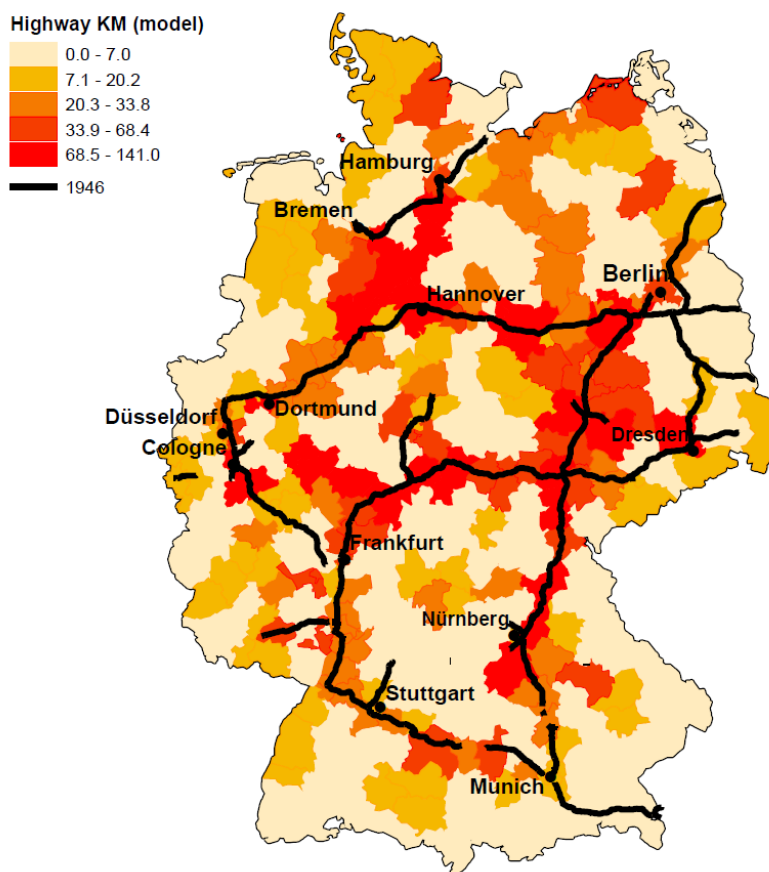
**A) Domestic Imports,  $Rsq= 0.35$ ,  $corr=0.59$**



**B) Domestic Exports,  $Rsq= 0.50$ ,  $corr=0.70$**

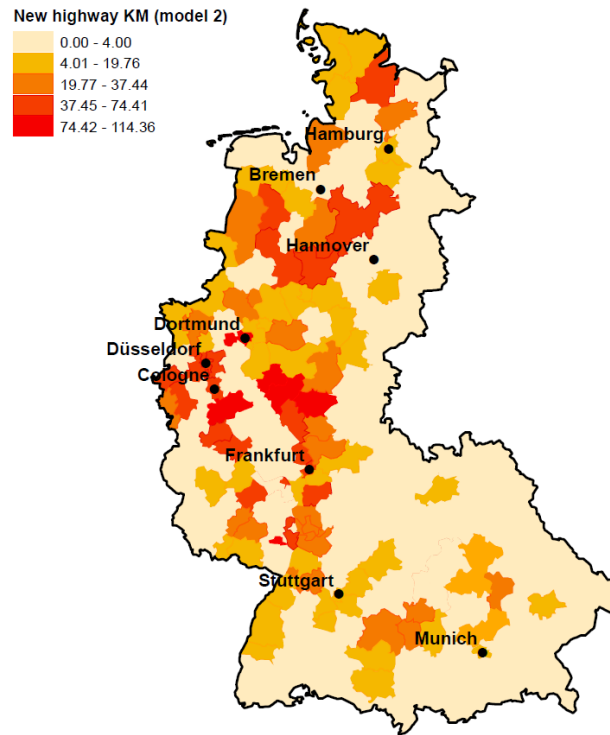
**Notes** Each dot represents one traffic-district, there are 18 in total. Data comes from the Statistical Yearbook of the Bundesrepublik, year 1940. The road shipment data is collected in tons and split up by tons imported and tons exported to the rest of German districts.

FIGURE D.9: Simulated Infrastructure before the Division shock - Timing of Construction

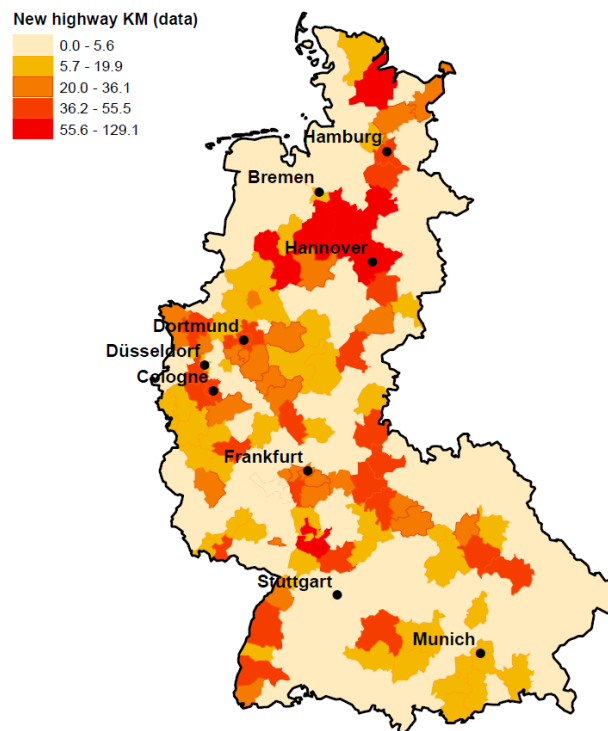


Notes: The shading represents the investment allocation by district, in terms of kilometres. The model predicts the optimal allocation of the investment budget to each district, as a share of the budget. I convert the share of investment into highway kilometres by assuming that the total number of kilometres built in the model is the same as in the 1930s Highway plan. The black lines represent the highways that had been built by 1946.

FIGURE D.10: Simulated Infrastructure investments after Division - International trade



A) Model (International trade)



B) Data (1974-1950)

**Notes:** The shading represents the change in investment allocation by district. The upper panel displays the changes predicted by the model while the lower panel represents the highway changes observed in the data (new highway construction between 1950 and 1974). Darker shades indicate higher highway construction.